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Low Wind Speed Turbine Project Phase II: The Application of Medium-Voltage Electrical Apparatus to the Class of Variable Speed Multi-Megawatt Low Wind Speed Turbines

June 15, 2004 — April 30, 2005

W. Erdman and M. Behnke
Behnke, Erdman & Whitaker (BEW) Engineering
San Ramon, California

Subcontract Report
NREL/SR-500-38686
November 2005

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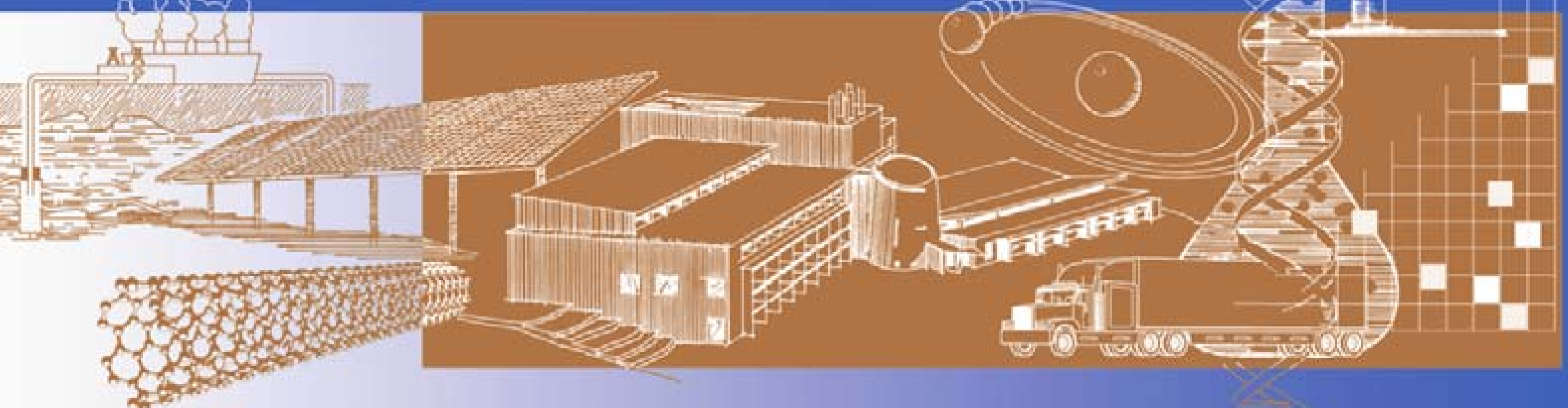

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1 Executive Summary

Kilowatt (kW) ratings of modern wind turbines have progressed rapidly from 50 kW to 1,800 kW over the past 25 years, with 3.0- to 7.5-megawatt (MW) turbines expected in the next 5 years. The premise of this study is simple: The rapid growth of wind turbine power ratings and the corresponding growth in turbine electrical generation systems and associated controls are quickly making low-voltage (LV) electrical design approaches cost-ineffective.

This report provides design detail and compares the cost of energy (COE) between commercial LV-class wind power machines and emerging medium-voltage (MV)- class multi-megawatt wind technology. The key finding is that a 2.5% reduction in the COE can be achieved by moving from LV to MV systems. This is a conservative estimate, with a 3% to 3.5% reduction believed to be attainable once purchase orders to support a 250-turbine/year production level are placed.

This evaluation considers capital costs as well as installation, maintenance, and training requirements for wind turbine maintenance personnel. Subsystems investigated include the generator, pendant cables, variable-speed converter, and padmount transformer with switchgear. Converter development is emphasized because significant savings can be realized here via engineering. Both current-source and voltage-source converter/inverter MV topologies are compared against their low-voltage, voltage-source counterparts at the 3.0-, 5.0-, and 7.5-MW levels.

Supplementary conclusions detailed within include:

- Perceived technical risk associated with the MV converter/inverter innovations is mitigated by the fact that such technology is already common in motor drive applications.
- There is a substantial reduction in the cost of pendant cables for the MV systems compared to LV systems.
- Transmission ride-through requirements will be a significant driver in the architecture of new systems. Voltage-source systems more naturally meet this requirement, but current-source systems with straightforward modifications will also meet the requirements.
- There is little or no cost difference between LV and MV generators or padmount transformers.
- Although component efficiencies within LV and MV designs differ, the overall efficiencies are the same.
- Installation costs are comparable for both system designs. With low voltage, many simple terminations are performed by less highly trained craft; fewer terminations are made at medium voltage by skilled craft at a 10% wage premium.
- LV vs. MV electrical equipment maintenance differences are more difficult to assess at this stage and are perhaps just a push. Regardless, the COE evaluations are not sensitive to such minor elements. In general, MV designs with substantially fewer parts are likely to require fewer unscheduled visits, albeit with more expensive labor.

2 Introduction and Scope of Study

Behnke, Erdman & Whitaker Engineering, Inc. (BEW Engineering) of San Ramon, California, prepared this report in support of the Low Wind Speed Turbine Project – Phase II projects for The National Renewable Energy Laboratory (NREL). The report documents the cost of energy (COE) impacts that result from the use of MV electrical apparatus on multi-megawatt-class wind turbines.

2.1 Project Team and Participants

Dr. William Erdman, Principal Investigator, and Michael R. Behnke, Principal Engineer, of BEW Engineering Inc. led this study. Clipper Windpower provided wind turbine application requirements, and DeWolf Engineering provided details on magnetics and mechanical structures.

The companies listed in Table 2-1 provided significant technical, operations and maintenance, and cost input to this study. These companies were asked to participate because of their wind energy history and experience and because of their unique expertise and product offerings, as noted in the right column.

Table 2-1 Companies Consulted

Company	Expertise
ABB	Power Semiconductors Electrical Control Apparatus and Switchgear
Areva T&D	Padmount Transformers
Mag-Tran Equipment Corp.	Magnetics
Okonite Inc.	Low- and Medium-Voltage Conductors
Potencia de Mexico	Low- and Medium-Voltage Generators
Powerex Inc.	Power Semiconductors
Quality Transformer	Magnetics
R – Theta	Thermal Management
Rotech	Power Semiconductor Custom Bus Bar
Square D	Electrical Control Apparatus and Switchgear

2.2 Premise of the Study

The premise of this study is simple: The rapid growth of wind turbine power ratings and the corresponding growth in turbine electrical generation systems and associated controls are quickly making low-voltage electrical design approaches cost-ineffective. This study examines the use of MV equipment on multi-megawatt turbines in contrast to, and as an alternative to, low-voltage-class systems.

Figure 2-1 shows the growth of wind turbine ratings from 1980 to 2010—essentially the history of modern wind energy systems. The log scale y-axis amplifies the rapid rise in power rating over this period. The figure represents commercial turbines in utility-scale, land-based, and offshore wind farms. A non-exhaustive sample of representative commercial turbines is also shown. In 2005, for example, a typical land-based turbine would have a rating of 1.5 MW to 1.8 MW, and offshore turbines would have a rating of 3.6 to 5.0 MW. Turbines on a scale of 7.5 MW are being considered for future offshore projects. A review of research turbines would suggest that single prototype turbines of a given kW rating are typically installed 2 to 3 years ahead of the time period depicted by the data shown in the figure.

This 30-year history helps to explain the preference for LV equipment, as purchasing procedures and operational and maintenance processes are skewed toward this equipment class. It also explains in part the continual reluctance of turbine manufacturers and wind plant operators to move toward MV solutions. A perceived increase in technical risk related to system design (particularly with variable-speed turbines) and uncertainty regarding increased operational and maintenance costs are often cited as reasons to not introduce MV equipment.

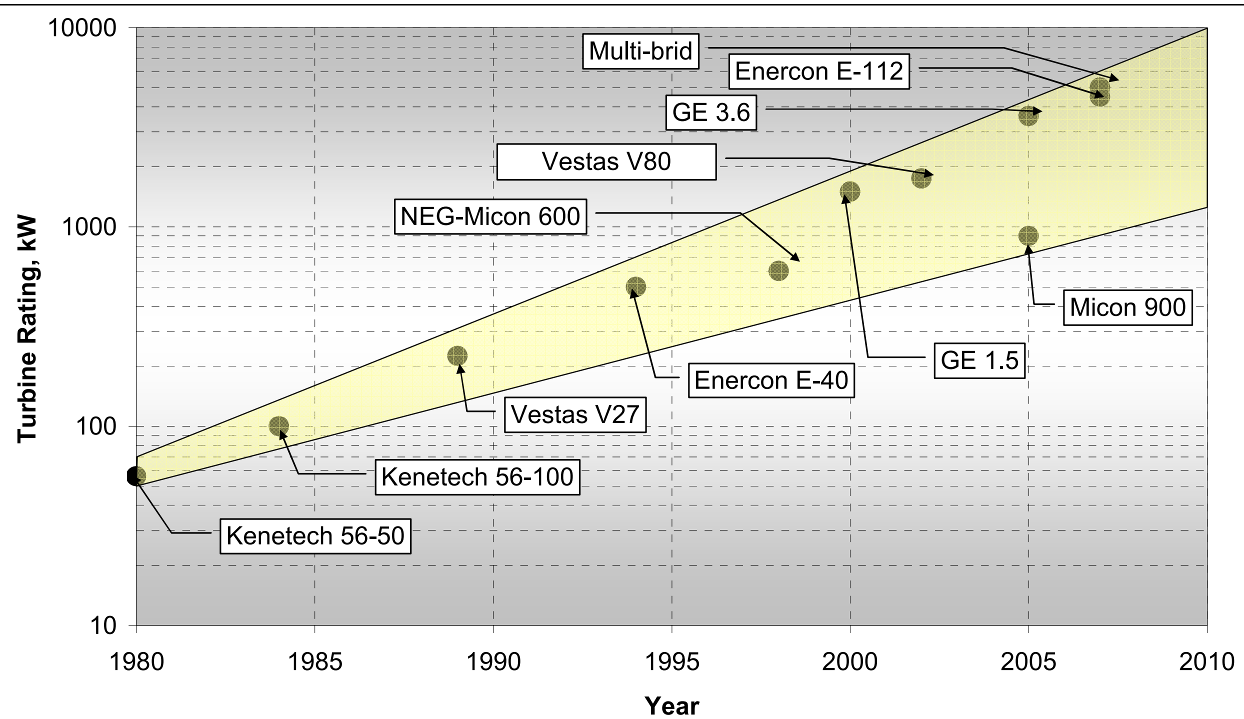


Figure 2-1 Wind turbine rating growth 1980-2010

In this study, we determined that the most cost-effective range for LV equipment tops out at about 750 kW. This conclusion is consistent with the major industrial switchgear and drive suppliers (Figure 2-2). Determining the "sweet spot" for LV equipment is of course an ever-changing, complicated task because of product requirements, product demand, introduction of new power semiconductor technology, and other factors. This 750-kW rating is at the top of the range for readily produced, readily available switchgear, conductors, and power semiconductors before paralleling of components begins.

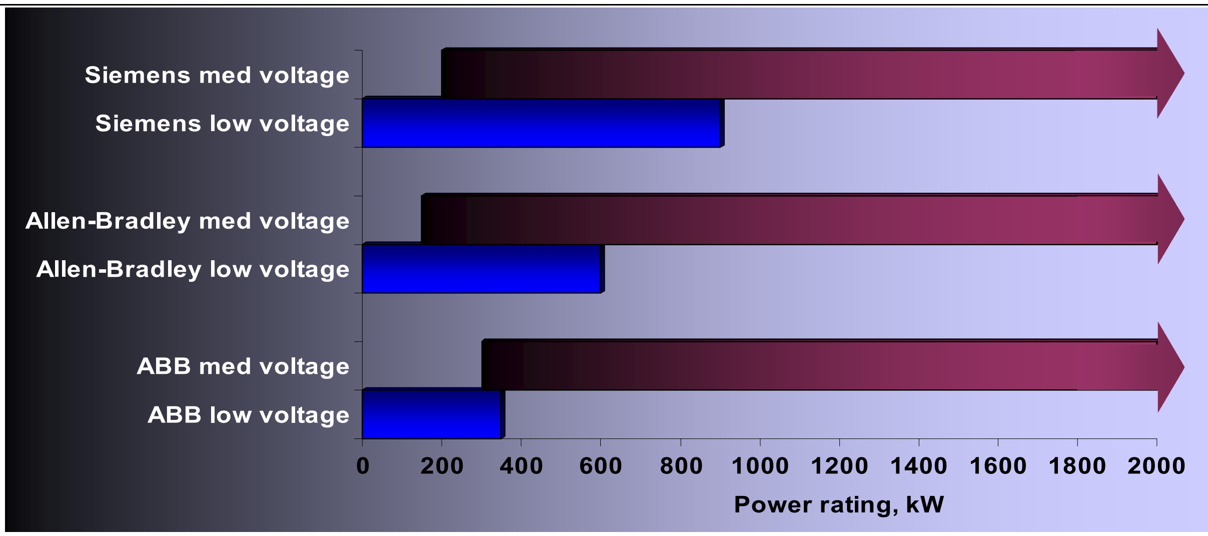


Figure 2-2 Sample standard drive product offerings

2.3 Definitions of LV and MV Classes

Definitions of three-phase LV and MV classes are regional and are based on applicable standards. A summary of the North American and European markets, the appropriate standards, and the corresponding definitions is given in Table 2-2.

Table 2-2 Regional voltage classifications

Region	Relevant Standard	Definition
North America	ANSI C84.1	Low voltage, below 600 V ○ 208 V, 120/240 V, 480 V, 575 V Medium voltage, above 600 V, below 35 kV ○ 2.4 kV, 4.16 kV, 6.9 kV, 12.47 kV, 13.8 kV, 21 kV, 34.5 kV
Europe	IEC 60038	Low voltage, below 1000 V ○ 220 V, 400 V, 690 V Medium voltage, above 1000 V, below 35 kV ○ 3.3 kV, 6.6 kV, 11 kV, 22 kV, 33 kV

In recent years, regional voltage-class distinctions have blurred. As the kilowatt rating of turbines has increased, for example, European manufacturers have installed 690-volt (V) electrical systems in the United States. With this approach, however, there are hidden costs associated with installation and maintenance. In many cases, common inspection standards simply don't address this voltage as it falls into a "grey" area (i.e., somewhere between low and medium voltage) and is subject to widely varying interpretations by the authority with jurisdiction from installation to installation. For this reason, certification and inspection become lengthy and costly when compared to well-defined and more commonly used electrical-system voltages. From an operation standpoint, inventories must increase to account for 1000-V-rated switchgear and apparatus that are not readily available through U.S. distribution channels.

Despite these hidden costs, the decision to install these non-standard, marginally higher-voltage electrical systems is driven by the fact that increasing turbine sizes are no longer well suited to strictly defined LV systems.

MV equipment is typically part of almost every utility-scale wind plant today. Historically, wind plant collection systems have operated at 12.47 kV and 13.8 kV in North America, but more recently collection systems are being installed at 34.5 kV. Maintenance on the collection system is often performed by personnel with higher electrical qualifications than that required for working on the LV turbine, at an estimated base pay differential of about 10%[1].

2.4 Electrical System and Turbine Architecture Considerations

This study uses existing turbine architecture to arrive at the COE for LV and MV systems. The architecture of the turbine and corresponding electrical system is described below.

2.4.1 Turbine Electrical System

Turbine components identified in red in Figure 2-3 are the primary focus of this study. These capital cost items, which will be subjected to trade-off studies, include the following:

- Generator
- Tower pendant cables (including festoon cables)

[1] Based on two sources: California 2005 prevailing wage data for Contra Costa County show the fully loaded, straight time rate for a journeyman cable splicer as 9.5% higher than that of an inside wireman; also, a March 25, 2005 consultation with a Pacific Gas & Electric senior electrical substation engineer indicated the labor cost for medium-voltage linemen was about 10% more, roughly $5/hr, than for low-voltage technicians.

- Converter, which comprises
    - Generator rectifier (up-tower or down-tower)
    - Inverter system
- Padmount transformer and switchgear.

To the extent these electrical items are used on an entire universe of turbine architectures — i.e., stall regulated, variable pitch, two bladed, three bladed, etc.— the results of this study are quite general and are widely applicable to many turbines.

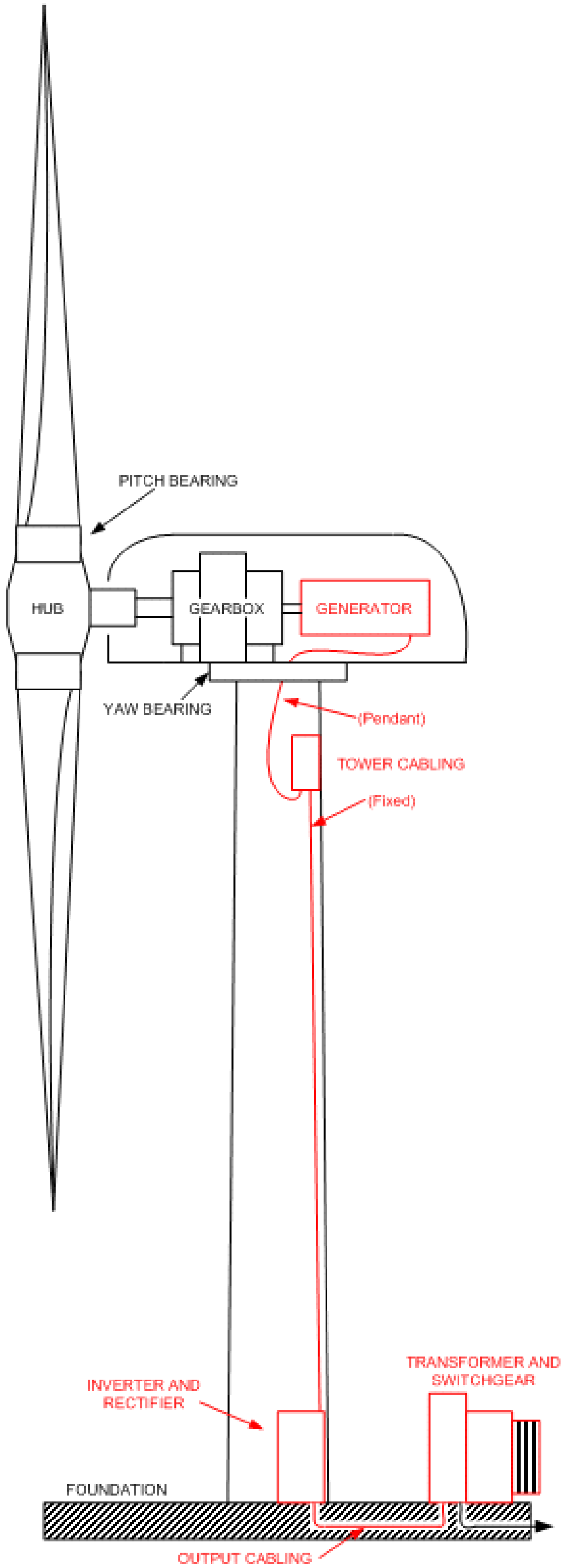


Figure 2-3 Wind turbine key components, with electrical system under consideration in red

2.4.1.1 Generator and Drive Train Efficiency

A classical synchronous generator with sinusoidal distributed windings is used with each of the turbine systems presented in this study. Both wound-field and permanent-magnet type machines are acceptable; in the COE estimates, the wound-field machine is used. Further, it is assumed that the wound-field machine is excited with constant main field current so that a constant Volts/Hz (open circuit) is achieved. There are no assumed damper windings; the generator is wound as a three-phase machine, and a synchronous reactance of 33% is selected. The selection of this reactance is consistent with references [1], [2], [3]. Further, it is assumed the power curve is operating over a speed range of 1.6:1. With this speed range and with the synchronous reactance at 33% and the generator connected to a six-pulse rectifier, the operating DC generator voltage for the LV system is as shown in Figure 2-4, below. MV generators will have similar shape and relationship and will be scaled appropriately.

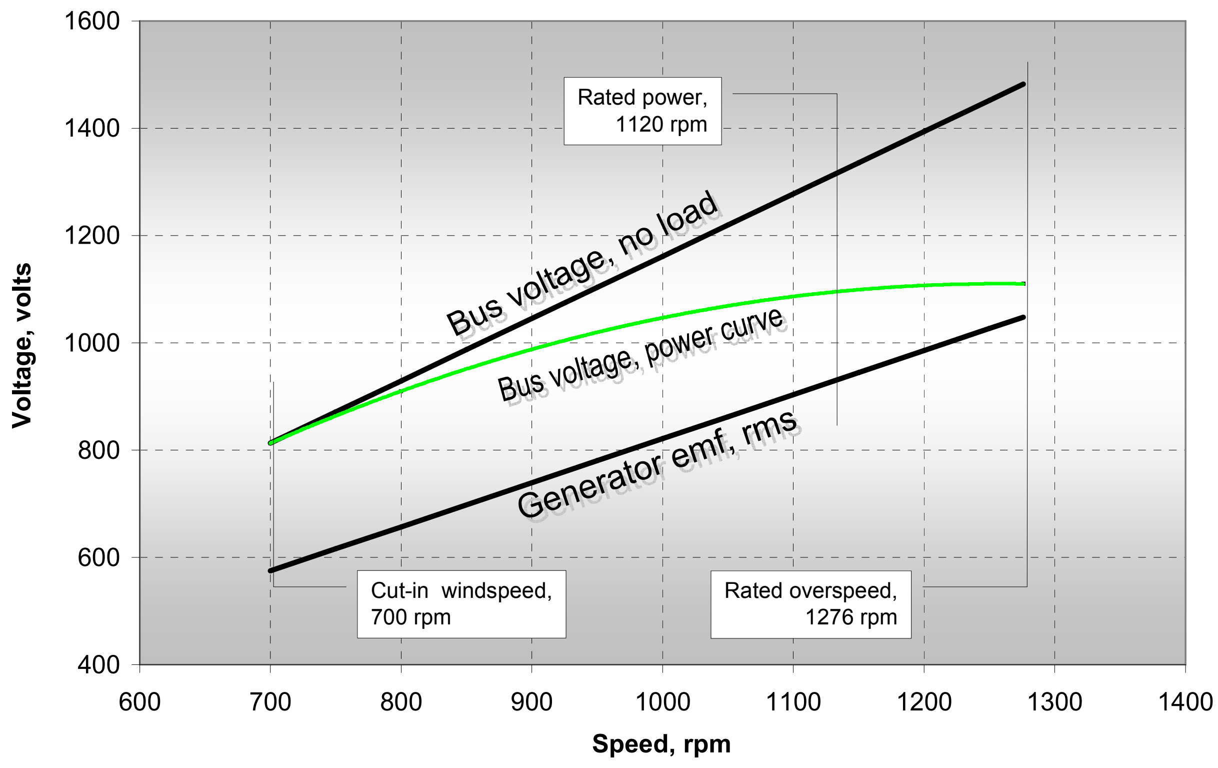


Figure 2-4 Generator DC bus voltage over a 1.6:1 operating power curve.

The selection of a synchronous generator is based on many requirements; however, one of the most compelling reasons to use this generator type is the recent introduction of transmission system ride-through requirements (see Section 2.6). With these new requirements, it is important to move the DC bus regulation function from the utility side of the converter to the generator side. The synchronous generator allows for this configuration.

It is further assumed that all generators will use a form-wound insulation system because of the ruggedness and added life expectancy this brings to the generator. Other advantages of preformed-insulation systems are better end-turn bracing and the ability to withstand higher rate-of-change of voltage (dv/dt). The cost impact of this decision really only bears on the LV designs in which the case for a random-wound generator could be made (but usually not in these kW classes). The random-wound machine would be less expensive than the form-wound machine, but random-wound insulation systems cannot be expected to have an adequate life expectancy. For the most part, the wind energy industry has settled on form-wound generators, and we use this assumption in this study.

Lastly, there is always a complicated tradeoff in generator selection between initial capital cost and efficiency. This tradeoff is not undertaken in this study as it will not impact the comparison between LV and MV systems; i.e., a 97% full load efficient generator can be achieved in low voltage or medium voltage. COE calculations use the total drive train efficiency shown in Figure 2-5.

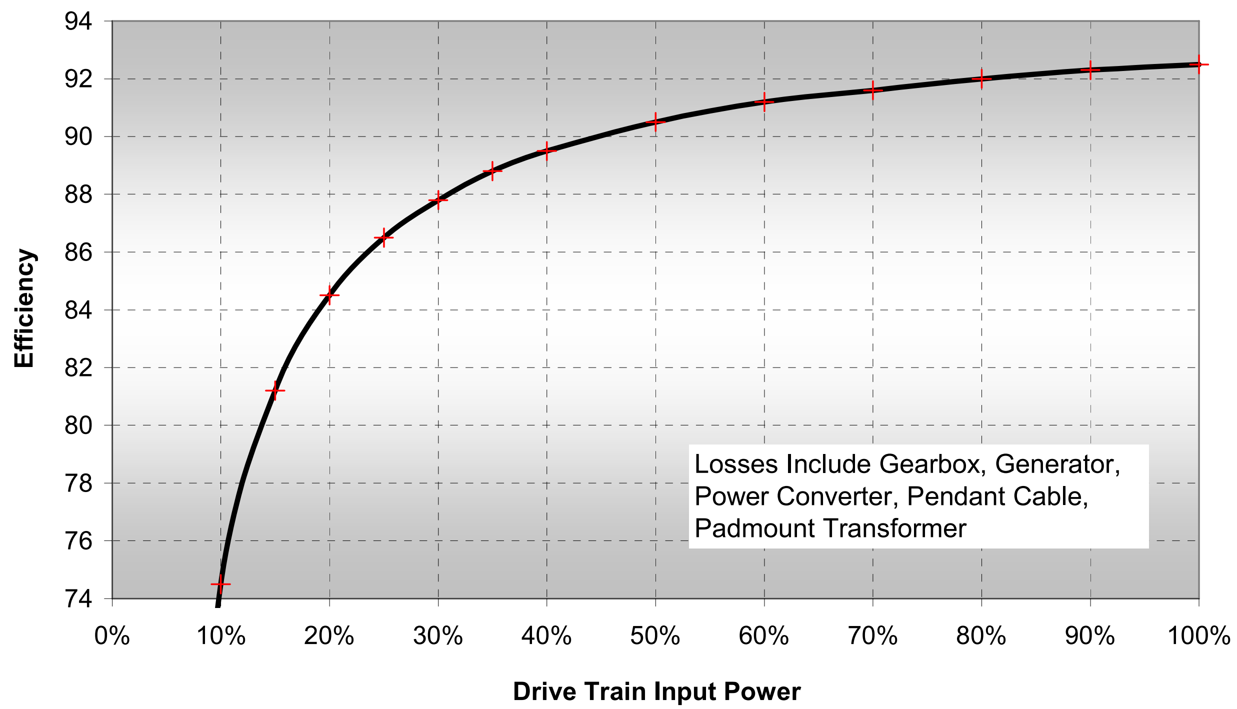
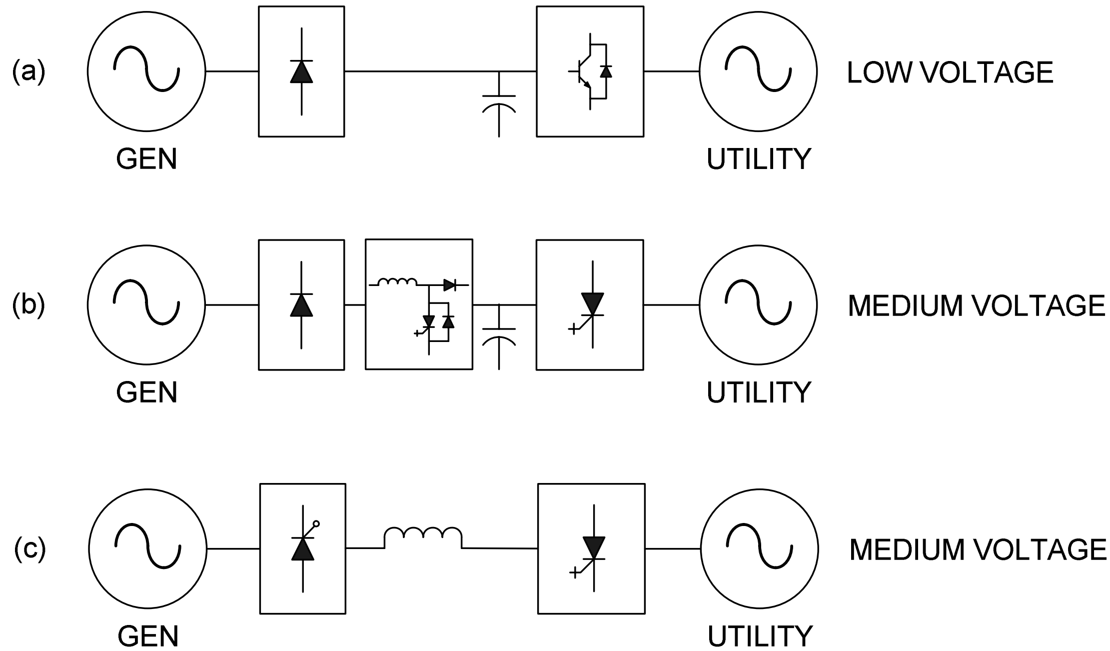


Figure 2-5 Drive Train Efficiency Curve

2.4.1.2 Generator Rectifier and Inverter System (Converter)

In this study, a six-pulse rectifier is assumed for all converter configurations and turbine power ratings[2]. Beyond the passive rectifier portion of the generator, the exact circuit topology depends on the selected voltage level and type of inverter system, either voltage-source or current-source. Three types of systems are under consideration (Figure 2-6).



(a) low-voltage passive rectifier and six-element voltage-source inverter,
(b) medium-voltage, neutral-point clamp, three-level, voltage-source inverter with passive rectifier and boost chopper on generator,
(c) medium-voltage with phase-controlled rectifier and current-source inverter

Figure 2-6 Systems under consideration

The LV system in Figure 2-6 (a) allows the DC bus voltage to fluctuate over the 200-V range (approximately) shown in Figure 2-4. The system is extremely simple, but it does require that the inverter withstand the highest voltage corresponding to the unloaded, maximum speed of the turbine. In LV systems up to 575 V, this small penalty is offset by the simplicity of the design.

The MV system shown in Figure 2-6 (b) uses a three-level (or multi-level), neutral point clamped, voltage-source inverter. This type of inverter system has become very popular in

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2 The use of a twelve-pulse rectifier with a six-phase generator is an option and even likely at 7.5 MW. Such a generator would have nearly the same active material but with stator and rotor pole pitch appropriate for six phases. The use of such a generator and rectifier would not substantially affect COE estimates. Ong, C., "Dynamic Simulation of Electric Machinery: Using Matlab/Simulink," Prentice-Hall, 1998.

MV systems in other applications [4], and its operation is discussed in references [5], [6]. This system uses a boost chopper on the generator side to step the DC voltage up to its required level for operating the inverter. The chopper in (b) extends the speed range of the generator down to near zero RPM. Also, because of the ride-through requirements (discussed in Section 2.6), the utility cannot be counted on to regulate the DC bus voltage, so the chopper serves this function as well.

Both (a) and (b) are voltage-source inverters and, as such, they operate in a mode at which the DC bus must be above the peak of the AC line-line voltage. When a utility line voltage dip occurs, these inverters naturally deal with the drop in voltage because the DC to AC requirement is not violated. These inverters can seamlessly and gracefully supply current to a utility fault and during the voltage recovery. The voltage-source inverters' power semiconductor devices are either insulated gate bipolar transistors (IGBTs) with fly-back diodes or asymmetrical gate-controlled thyristor devices [7], [8].

The MV system in Figure 1-6 (c) uses a current-source inverter. This is fundamentally different from the voltage-source case. Proper operation of this system requires that the DC bus voltage be lower than the peak of the AC line-line voltage. For this reason, this system naturally extends the speed range of the generator right down to zero speed. During a ride-through event, however, the AC line-line voltage drops substantially, and the DC bus voltage must be reduced or an uncontrolled fault current will occur. The phase controller rectifier shown on the generator only becomes active during this dip in the utility voltage. In normal operation the controlled rectifier is fired at a zero-degree delay angle, and it looks like a passive rectifier in this mode of operation. Symmetrical gate controlled thyristor devices are required for current-source inverters [7], [8].

2.4.1.3 Tower Pendant Cables

Figure 2-7 shows a 600-V and 5/8-kV class of conductor, either of which would be acceptable for tower pendant cables.

Figure 2-7 Tower pendant cables *(left)*, 600-V class low voltage and *(right)* 5/8-kV class MV conductors.

The LV cable shown on the left in Figure 2-7 has two parts, the coated copper conductor and a simple insulation system. In this case the insulation consists of a black pigmented ethylene-propylene base insulating compound. The cable is rated at 90 °C, is flame-retardant, and is suitable for indoor and outdoor applications. The conductor is relatively easy to terminate and install. Conductors of this type are available in sizes ranging from 14 gauge to 1000 MCM. At larger contemporary power levels in the 3.0- to 7.5-MW range, the chief disadvantage of this cable is simply its weight and volume.

The MV cable in Figure 2-7 is more complex. These cables have a coated copper conductor and a variety of insulation layers. Directly covering the conductor is a strand screen coated (ethylene-propylene compound) insulator. This is covered by another insulating layer of ethylene-propylene compound. A second coated stranding screen is then shown. A solid copper tape shield is then shown over the top of the insulating screen. Finally, a PVC jacket provides resistance to oils, acids, chemicals, and mechanical damage. Terminating this conductor is more complicated and requires more skill than that needed for LV cables. Care must be taken to avoid points or sharp turns that could result in high E-fields and resultant dielectric breakdown. These conductors are available in the same sizes as the LV cables.

While the terminations of these MV cables are more difficult than the LV cable and are usually performed by higher-skilled labor, there are far fewer terminations to make in a given turbine size. The total cost impact on installation and maintenance of these cables is minor and covered in the COE models in subsequent sections. Figure 2-8 compares low- and MV tower pendant cables for the smaller turbine under consideration, 3.0 MW and 5.0 MW.

As a last point, rigid aluminum buss was considered as an alternative for the copper tower pendant cables. These rigid buss alternatives are cited as being lower cost because of the reduced amount of labor required for installation. Our analysis shows no significant cost advantage for either and given the availability of MV building cable, the cable approach is expected to yield significant certification advantages. For these reasons, in this study standard building cable is used rather than rigid buss.

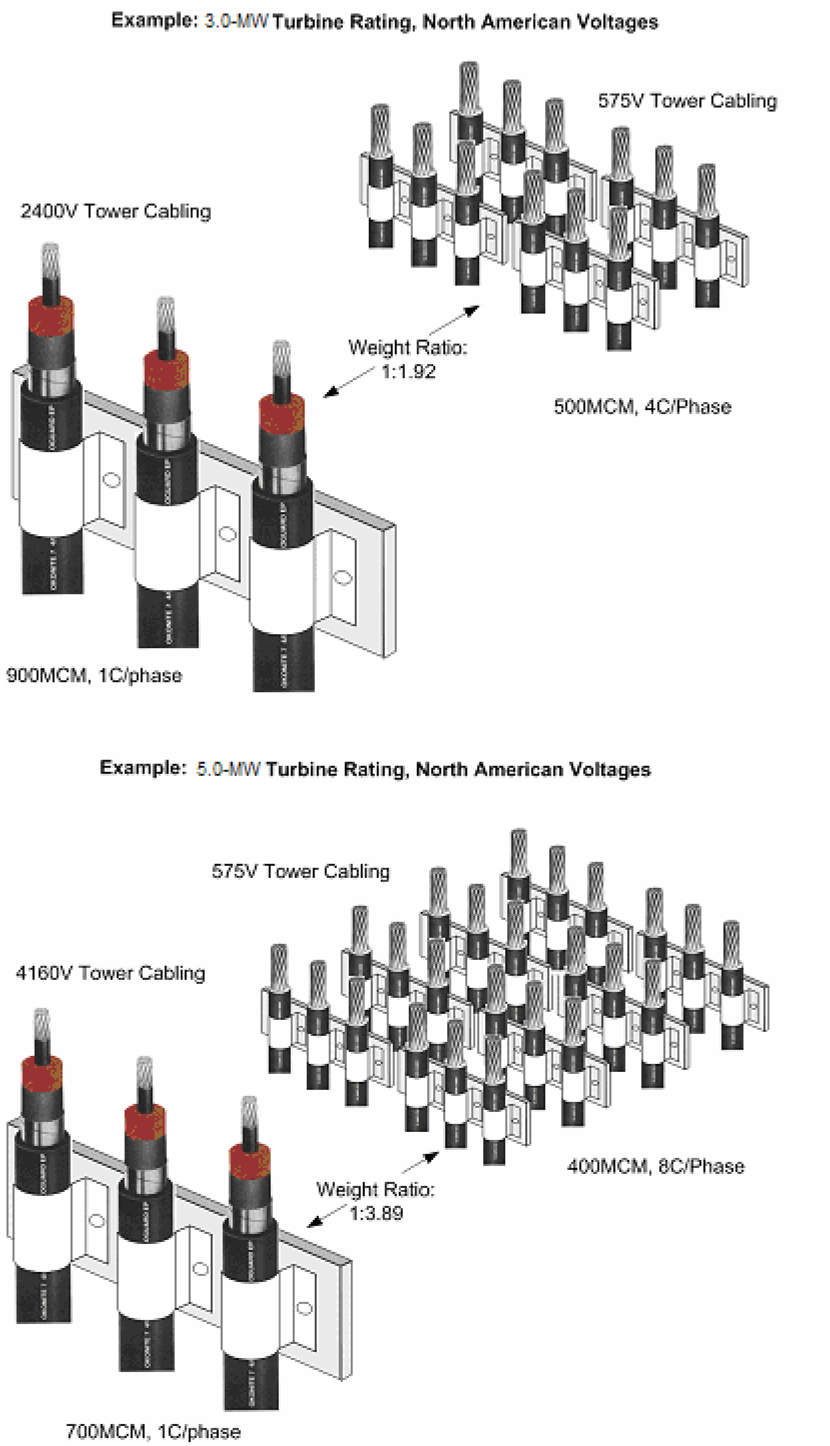

Figure 2-8 LV vs. MV tower pendant cables, 3.0 MW and 5.0 MW

2.4.1.4 Padmount Transformer and Main Breaker

The padmount transformers used in the LV and MV comparative studies are quite similar to the padmount transformers used on turbines in the past. A typical padmount transformer would be oil filled, closed container, with a 34.5-kV primary for the collection system and either 575 V or 2400/4160/6900 V for the turbine connection. Both voltage-class transformers are assumed to have a wye-wye winding for solid grounding of the neutral(s). Typical impedances will be in the 4%–7% range.

The main breaker for the transformer will be located in the padmount transformer or separately in the converter cabinet(s). An example of the size and weight of an LV breaker vs. MV main breaker at 3.0 MW and 5.0 MW is shown in Figure 2-9. The main LV breaker is substantially larger, heavier, and more costly than the MV counterpart.

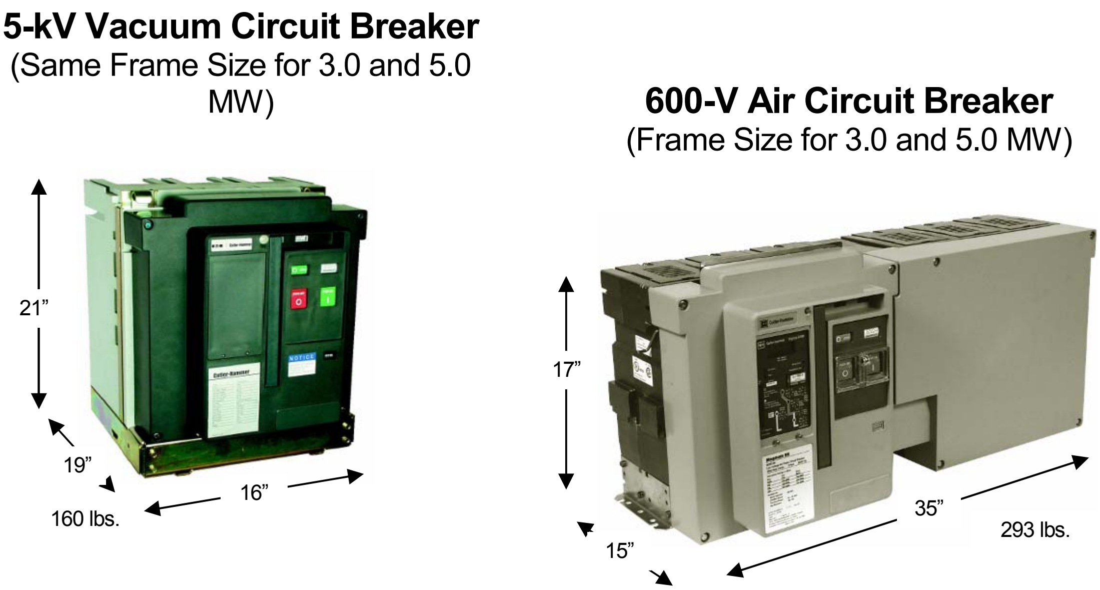

Figure 2-9 LV and MV main circuit breakers.

2.4.2 Turbine Architecture for COE Model

For purposes of COE calculations, a baseline turbine was used and scaled for different MW-class machines based on [9] and [10]. The assumptions used in the baseline are shown in Table 2-3 and Table 1-4. These characteristics were used to develop the baseline turbine and power rating derivatives thereof. In addition to the above-mentioned capital equipment items, the impact of MV electrical systems on installation costs and electrical operation and maintenance cost will be considered.

Table 2-3 Baseline turbine assumptions

Characteristic	Value
Number of Blades	3
General Configurations	Upwind Full-span pitch Rotor hub
Rotor Solidity	2% - 5%
Variable-Speed Operation	Maximum Power Coefficient = 0.47
Air Density	1.225 kg/m^3
Annual Mean Wind Speed	5.8 m/s, 6.7 m/s
Vertical Wind Shear	Power Exponent = 0.143
Rated Wind Speed	1.5 x annual average @ hub height
Cut-Out Wind Speed	3.5 x annual average @ hub height

Table 2-4 Baseline turbine, size-related operational assumptions

Characteristics	Rating			
	1.5 MW	3.0 MW	5.0 MW	7.5 MW
Rotor Diameter, m	69	98	126	155
Design Tip-Speed Ratio	7.0	7.0	7.0	7.0
Theoretical Operating Minimum RPM	13.9	9.8	7.6	6.2
Rated RPM	22.2	15.6	12.2	9.9
Maximum Operating RPM (1.07 Rated)	23.8	16.7	13.0	10.5
PE System Trip RPM (1.14 Rated)	25.3	17.8	13.9	11.2
Safety System Activation RPM (1.2 Max)	28.5	18.7	14.6	11.8
Maximum Over-Speed Design RPM (1.3 Max)	30.9	20.3	15.8	12.8
Hub Height, m	65	91	117	144
Cut-In Wind Speed, m/s	3	3	3	3
Cut-Out Wind Speed, m/s	26	26	26	26

2.5 Wind Energy Markets Considered in this Study

The principal market considered in this study is North America. Many of the conclusions expressed herein are extensible to Europe and the rest of the world, and where appropriate, we mention such extensions. One of the important and interesting discussions regarding geographic jurisdiction is the definition of low and medium voltage, as this differs from region to region. Worldwide classifications of voltage class and relevant standards were delineated in Section 1.3.

2.6 Materials Costing Volume Assumption

All costing performed in this study assumes annual production of 250 turbines. Further, it is assumed that this is a mature turbine production with at least 150 previously completed units.

2.7 Transmission Fault Ride-Through Requirements

Over the past 2 years, there has been a substantial change in how transmission operators deal with wind plants interconnected to the public electrical transmission system. In the early history of wind plants, interconnecting utilities required that turbines (and wind plants) drop offline in the presence of system faults and corresponding voltage dips. As wind plants begin to represent a higher percentage of generation on a given transmission system, the view of wind plants as a utility nuisance has changed to that of a system resource whose operation must be maintained through transmission system transients. This change in perspective has precipitated new requirements for how a wind plant should operate during transient conditions that would previously result in the plant tripping offline. These "ride-through" requirements continue to evolve and have significant impact on the design of the turbine and plant electrical systems, particularly for variable-speed turbines.

2.7.1 Recent Transmission Ride-Through Requirements

Beginning in early 2003, the German utility and transmission operator E.ON instituted a ride-through requirement for newly installed turbines. The standard required that turbines ride-through, rather than trip off, for transmission faults according to the voltage profile shown in Figure 2-10. The requirement was not fully developed, and it has been assumed that the ride-through requirement pertained to three-phase symmetrical faults–the worst condition from a stability standpoint for the transmission operator. The initial requirement did not mention non-symmetrical faults and did not specify whether the wind plant should feed the fault or stop supplying current during the fault event. Later in 2003, some ambiguities were addressed, and it became clear that feeding the fault was intended [11].

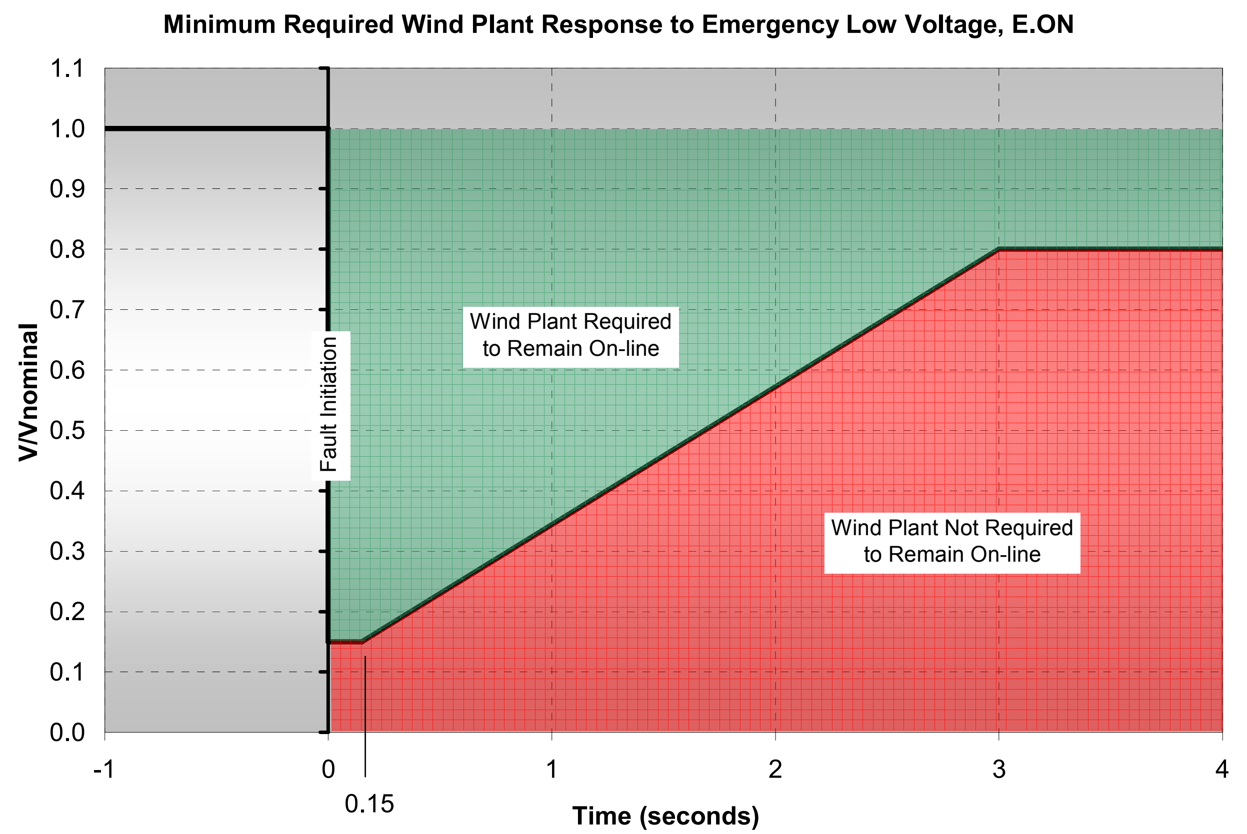

Figure 2-10 E.ON initial requirements for wind turbine ride-through posed in 2003

In 2004, the transmission operator in Spain, Red Eléctrica de España, proposed a similar, but modified curve to that proposed by E.ON. The curve shown in Figure 2-11 became a requirement for wind turbines installed in Spain in February 2005, and it is applicable to three-phase symmetrical faults and non-symmetrical faults [12].

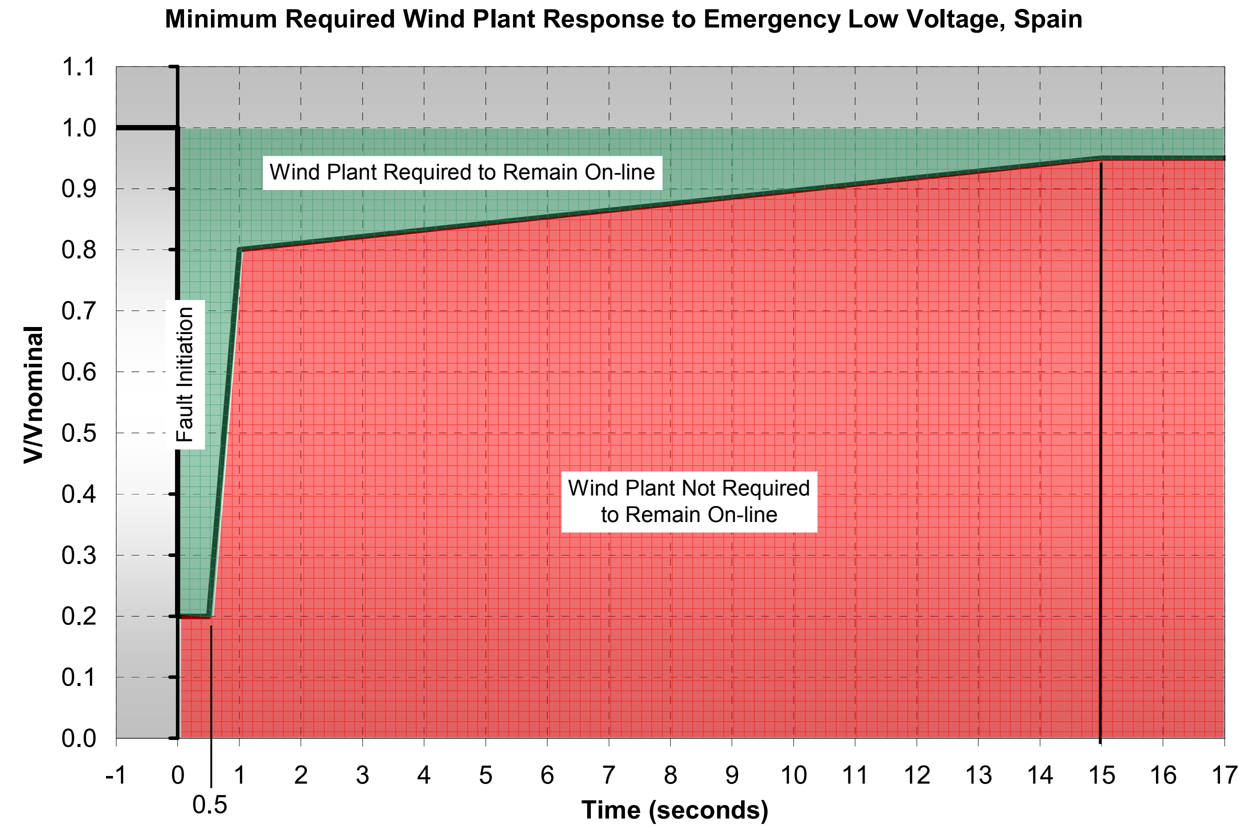

Figure 2-11 Spanish ride-through requirements proposed in spring 2004

In February 2005, the Federal Energy Regulatory Commission (FERC) proposed its own ride-through requirements (Figure 2-12). These requirements have been released for comment and should be finalized by the end of 2005. Clearly, the FERC-proposed requirements are more stringent than either of the European requirements because of the extended time period (625 ms) at very low AC voltage (15% of nominal).

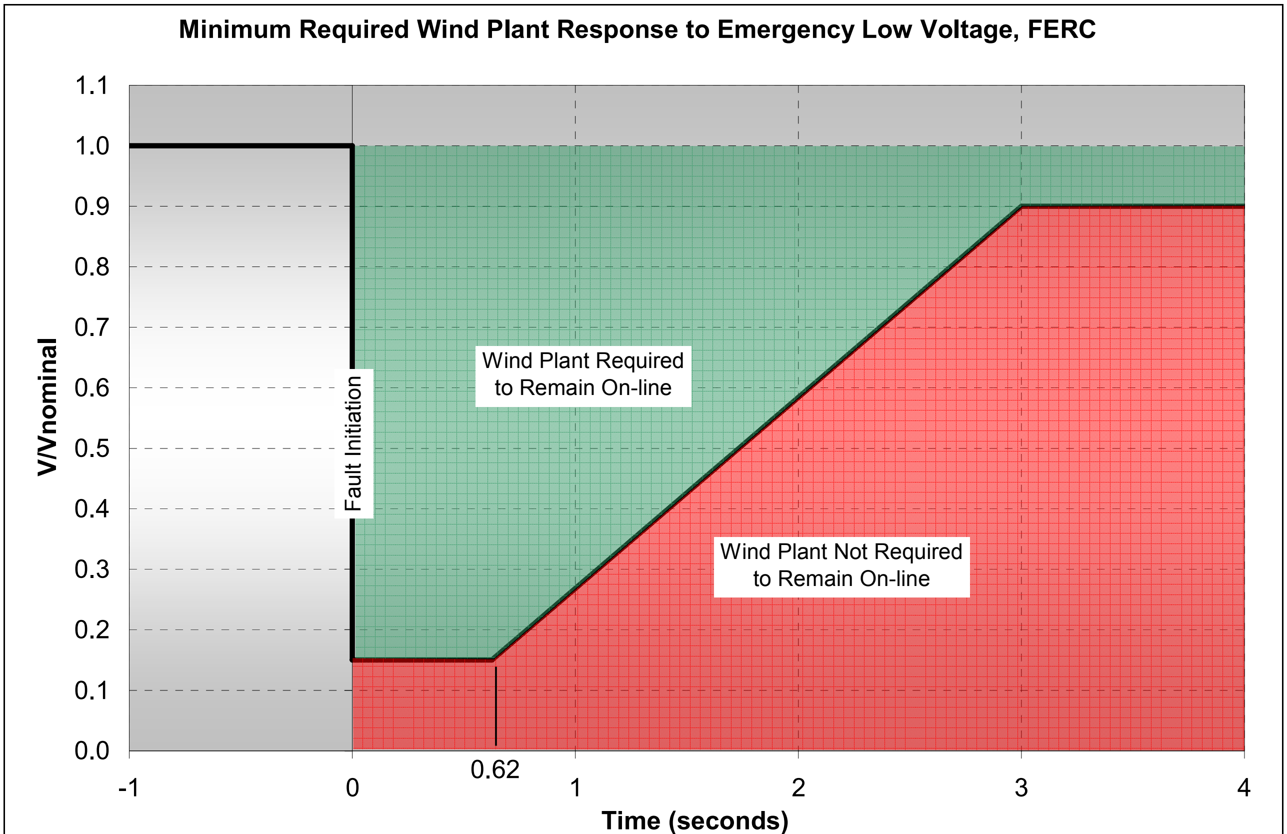

Figure 2-12 FERC ride-through requirements

2.7.2 Impact of Ride-Through Requirements on Electrical System

The ride-through requirements mentioned above have a significant impact on technology selection in both low- and MV wind turbine systems. Simple items such as control board power supply hold-up during the transmission faults become important. The ability of electrical pitch systems to operate under these LV conditions can also be problematic and for which this system ride-through requirement can be a significant cost driver.

Ride-through requirements have the largest impact on generator and variable-speed converter technology selection. In recent years, a popular approach to providing variable-speed operation has been to utilize a double-fed generator with a partially rated converter system connected to the generator rotor. This approach has been used somewhat effectively despite often-cited and obvious drawbacks[3]. One of the principal advantages of this approach is that it allows the use of LV converters and technology to provide the variable-speed feature, even on large turbines.

3 Drawbacks include slip ring assemblies and associated maintenance and large bearing currents due to rotor PWM excitation.

The problem with the doubly fed approach relative to the ride-through requirements is that it does not entirely decouple the generator operation from the utility system, as the stator circuit remains directly connected to the utility. Because of this direct connection, uncontrolled stator dynamics occur during the transmission fault and very high voltages can occur on the rotor circuit. This fault condition jeopardizes the LV converter and requires additional protective circuitry in the form of a crowbar. These stator transients that occur during a transmission fault and the consequential firing of the crowbar have also been cited as a main cause of gearbox problems as severe torque transients on the drive train can occur [13], [14], [15].

Figure 2-13 compares a simplified schematic representation of a doubly fed, partial conversion system to a full conversion system. Complete decoupling between the generator and utility is clear in the latter case. A full power conversion system that completely decouples the generator from the utility grid is a preferred approach to meet the ride-through requirements, as the resulting torque and current transients during a transmission fault are more readily controlled. Furthermore, extensive cost analyses have shown no advantage to the partially fed system over a full power conversion system when all costs of ownership are included. For these reasons, only full conversion systems are considered in this study.

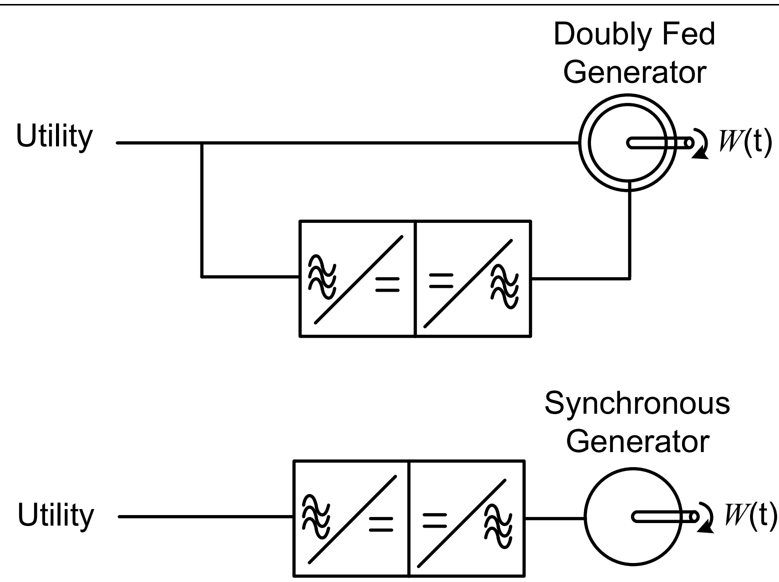

Figure 2-13 Doubly fed and full conversion system schematics

2.8 References

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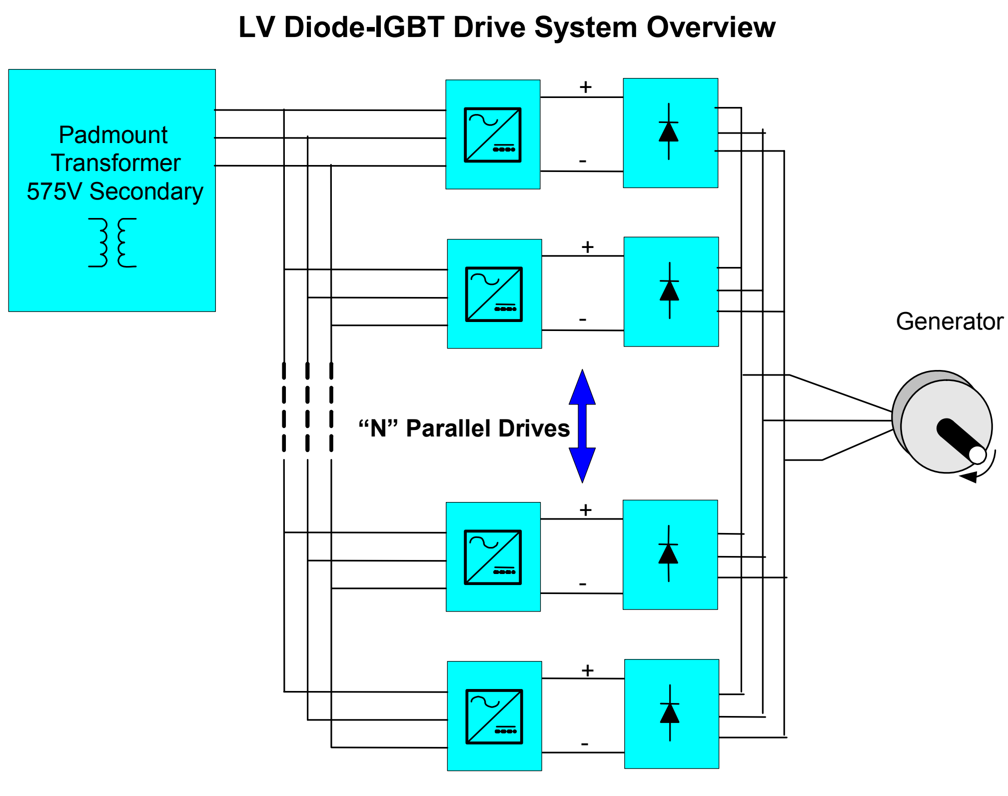
3 Electrical System Bill of Material – LV Voltage-Source Inverter Topology

This section details the electrical system Bill of Material (BOM) for the 3.0-, 5.0-, and 7.5-MW turbines using a North American, LV, 575-V electrical system. Beyond the entire electrical system cost, which is used for COE comparison purposes, the converter for each of the turbine ratings is detailed out. The 3.0-MW converter is presented in the greatest detail, showing both simplified schematics and full costed BOMs. The 5.0- and 7.5-MW systems are described using the same method, but because these systems simply represent more paralleling of the same 3.0-MW components, they are presented in somewhat less detail to minimize overlap and repetition from the 3.0-MW system. As noted in the previous section, the most common method of designing a multi-MW converter involves paralleling enough LV voltage-source inverters to achieve the desired rating. The generic design for all three systems is shown in Figure 3-1.



System MW	"N" Drives	kW/Drive
3.0	4	750
5.0	8	625
7.5	10	750

Figure 3-1 Generic LV converter system diagram

3.1 Section Organization

The section is organized as follows.

Section 3.2:	An electrical system BOM is presented that represents the costing of all electrical system components under consideration and as described in the introduction of Section 1.
Section 3.2.1 -2.2.3:	Converter pricing. The converter assembly is selected for detailing because it is custom engineered, has a significant cost impact on the electrical system, and has the most opportunity for reducing cost. Subsections under this assembly include a system diagram and a price spreadsheet. The spreadsheet includes material costs, direct labor costs, indirect costs, and gross margin for the converter manufacturer. With this information, the converter appears in the highest level electrical system BOM as a purchased item.
Sections 3.2.4 - 3.2.8:	These include a rolled-up converter BOM along with subassembly BOM breakdowns, in the following order: o Complete assembly o IGBT matrix subassembly o Line filter subassembly o Subpanel subassembly o Rectifier subassembly
Sections 3.3 - 3.4	Follow the above pattern for 5.0- and 7.5-MW systems with certain redundant subassembly drawings and subassembly BOMs excluded.

The generator is not detailed in this study. The cost of the MV generator is essentially the same as the LV generator when form-wound insulation systems are used throughout. A slight adder for the higher voltage insulation systems (4160V, 6900V) is reflected where appropriate in the BOM.

3.2 Electrical System BOM for 3.0-MW LV Turbine

Table 3-1 lists the electrical system BOM for the 3.0-MW, LV turbine. The material cost totalized at the bottom of the table will be compared with the MV designs in the COE models of Section 5.

Table 3-1 3.0-MW LV electrical system BOM

#	Item	Description	Cost
1	Generator	3.0 MW, 105 Deg. C rise, 6 pole, open drip-proof, flange mounted, 33% reactance, wye connected, form wound, 97% F.L. efficiency	$ 114,000
2	Tower Pendant Cables	3249 ft. of 2kV, 90 deg C., 350 MCM,normal stranding	$ 18,932
3	Tower Pendant Cables (festooning)	573 ft., 2 kV, high stranded, 313 MCM DLO	$ 3,712
4	LV Inverter	Voltage source inverter per attached included BOM's	$ 139,275
5	Transformer and Switchgear	3MVA, Oil filled padmount, outdoor rated, 34.5 kV primary, 575 V wye secondary	$ 34,318
		Total Cost	$ 310,237

3.2.1 Converter System for 3.0-MW LV Turbine

The 3.0-MW, LV variable-speed converter system consists of paralleled passive rectifier and IGBT inverter assemblies. As discussed earlier, a limit of 750 kW represents the maximum cost-effective approach to LV converters in each assembly. For this reason, four 750-kW converters, operating in parallel, are used in the 3.0-MW turbine. This configuration is shown in the simplified schematic of Figure 3-2. Note that one control board controls all four converters. Line filter and switchgear are not included in this simplified figure; these are described in more detail in subsequent figures and sub-sections.

3.2.2 Converter System Diagram for 3.0-MW LV Turbine

The figure below shows the paralleled structure of four LV converters used to build up a 3.0-MW complete converter system.

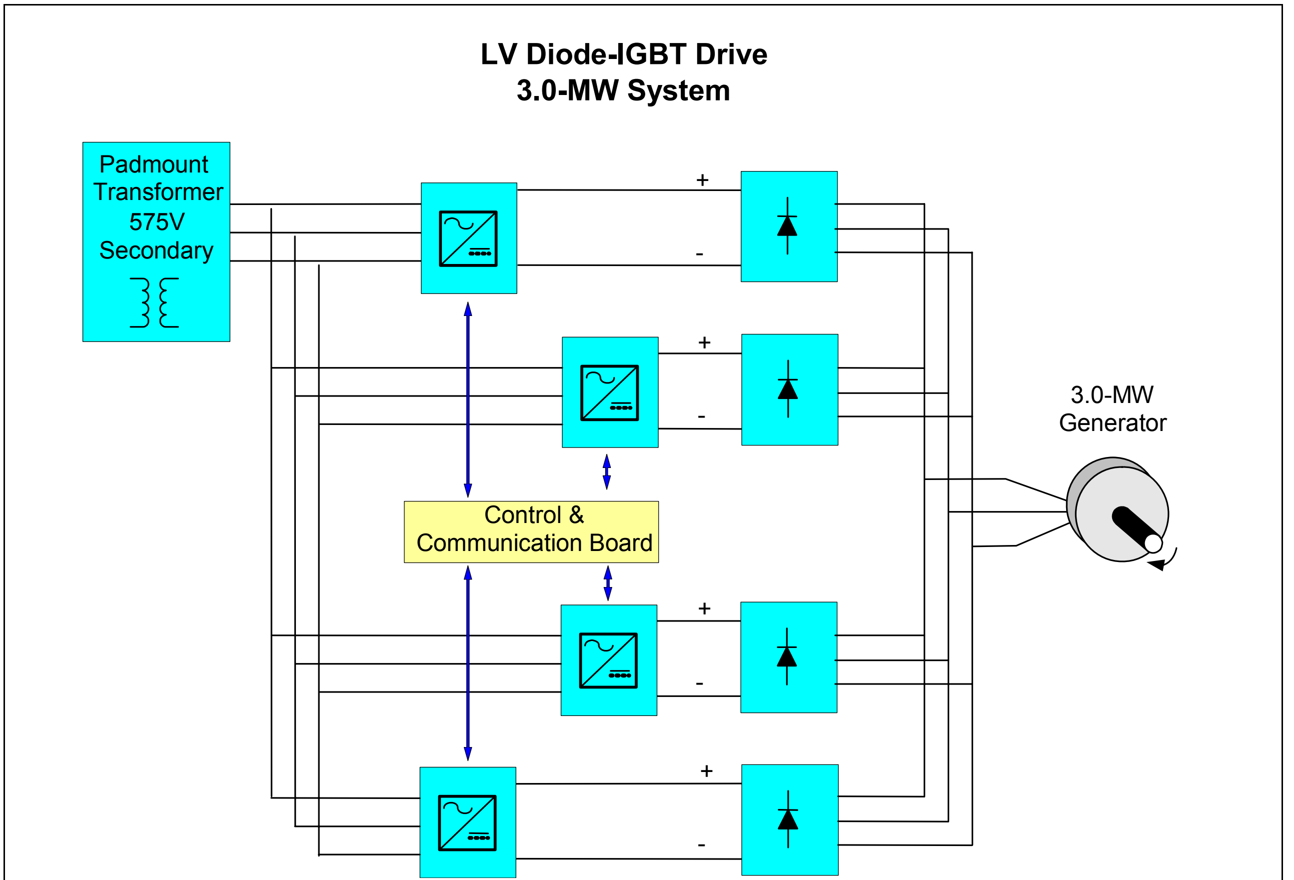


Figure 3-2 Converter system diagram for 3.0-MW LV turbine

3.2.3 Converter Pricing Spreadsheet for 3.0-MW LV Turbine

The converter pricing spreadsheet below delineates total material costs, direct fixed and variable costs, and a gross margin ranging from 20% to 30% for the converter manufacturer. In addition to the material costs detailed in subsequent sections, an additional $1328 must be added for the one control board not identified in any assembly or subassembly BOM. Other important footnotes are included at the bottom of the spreadsheet. Attention should be given to footnote #4. This is the annualized cost of building converters regardless of the quantities built (therefore it is a direct fixed cost). This includes manufacturing space, rent, utilities, and work floor supervision. This number will vary depending on the converter MW rating mostly because of utility billings.

Table 3-2 Converter pricing spreadsheet for 3.0-MW LV turbine

3.0-MW LV Synchronous Machine Drive						
Direct Variable Materials[1]	$	95,856.54	$	95,856.54	$	95,856.54
Direct Variable Labor[2]	$	6,871.43	$	6,871.43	$	6,871.43
Direct Fixed Costs[3]	$	1,728.00	$	1,728.00	$	1,728.00
Total Direct Costs	$	104,455.97	$	104,455.97	$	104,455.97
Gross Margin[4]		20%		25%		30%
Sales Price	$	130,569.96	$	139,274.62	$	149,222.81

(1) Annual production = 250 Turbines
(2) Includes 3% freight in
(3) Assumes 70% utilization and 30% fringe benefits
(4) Includes $120k rent, $200k capital equip, $27k utility and $85k supervision (annual cost)
(5) Gross Margin = (Sales Price - Direct Cost)/Sales Price

3.2.4 Converter Material Breakdown and BOM for 3.0-MW LV Turbine

As introduced in Section 3.1, material cost for one converter main assembly is listed below, with subassembly details shown in the subsequent four sections. The "Quoted" column is included to show fixed quoted costs from the various selected vendors. A "Y" indicates an off-the-shelf component for which a quote was obtained. "N/A" indicates a custom subassembly for which costs estimates were prepared by the project team and detailed separately.

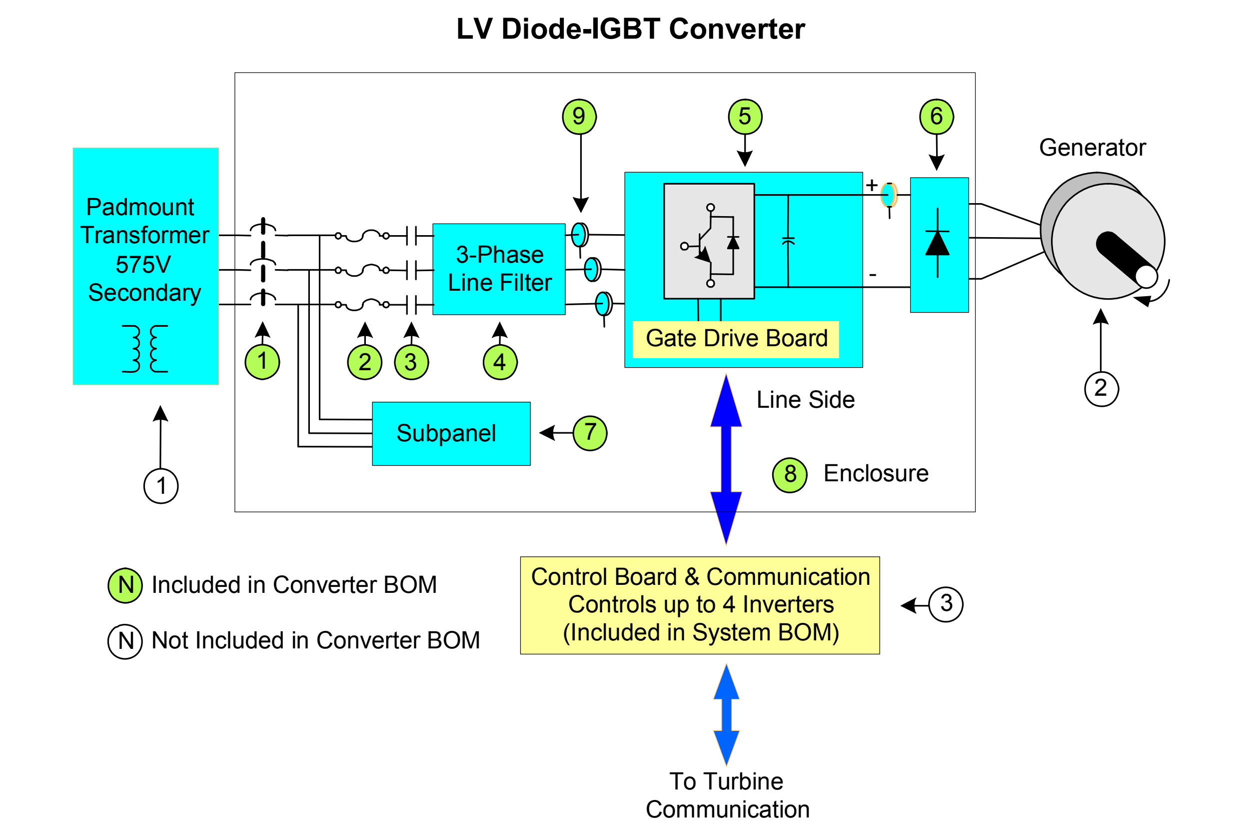


Figure 3-3 Converter diagram for 3.0-MW LV turbine

Table 3-3 3.0-MW LV Converter BOM

LV 750 kVA Converter BOM

Item #	Qty	Description	Quoted	Unit Cost	Ext Cost
1	1	Circuit Breaker, 1000A, 600VAC, 3-P, Line	Y	1,500.00	1,500.00
2	1	Fuse, 800A, 600VAC, 3-Pole	Y	120.00	120.00
3	1	Contactor, 800A, 600VAC, 3-Pole, Line	Y	1,300.00	1,300.00
4	1	Line Filter, 3 Phase	N/A	6,340.00	6,340.00
5	1	Assy, IGBT Matrix, 3-Phase, Line	N/A	7,293.00	7,293.00
6	1	Diode Bridge	N/A	2,463.00	2,463.00
7	1	Sub Panel	N/A	2,038.40	2,038.40
8	1	Enclosure	Y	1,100.00	1,100.00
9	4	Current Transducers, Line	Y	195.00	780.00
		TOTAL:			**22,934.40**

3.2.5 Line Matrix for 3.0-MW LV Turbine

The inverter matrix for the 3.0-MW converter is diagramed below. It is a six-element, IGBT-based, two-level inverter using 2.5-kV silicon devices.

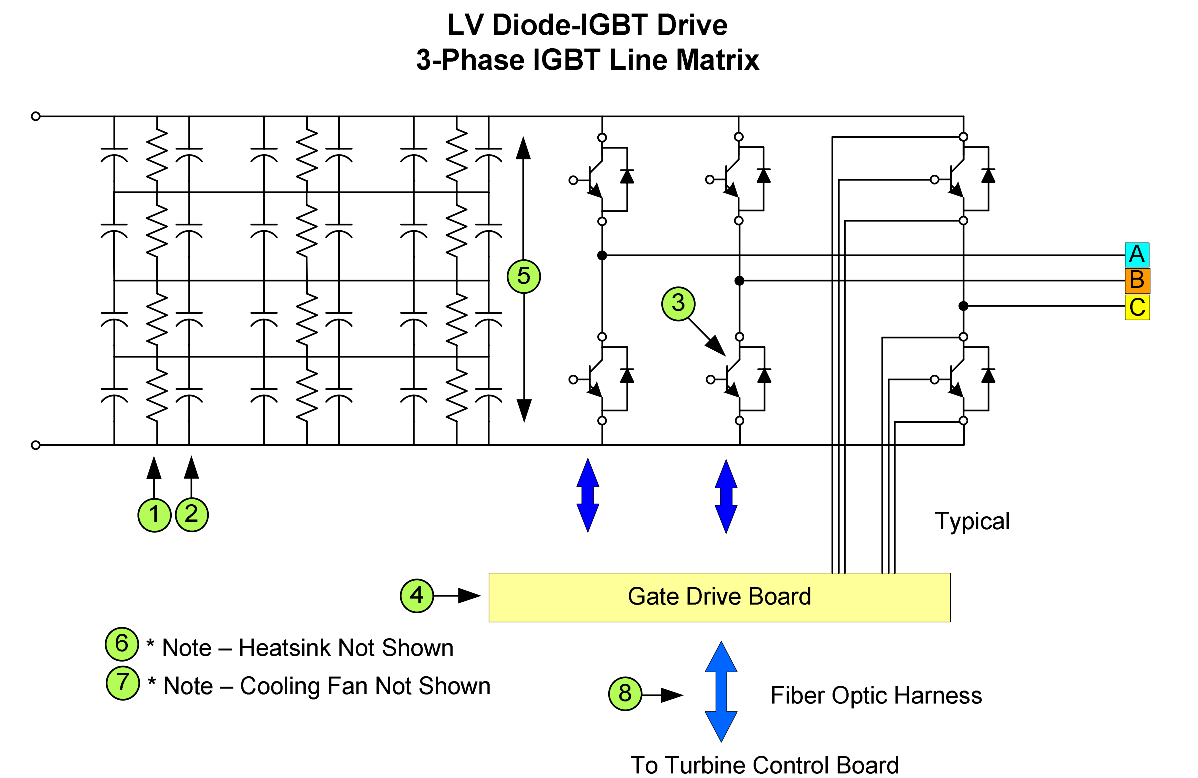


Figure 3-4 Line matrix schematic, 3.0-MW LV turbine

Table 3-4 Line matrix costing, 3.0-MW LV turbine

LV 750 kVA Line Matrix BOM

Item #	Qty	Description	Quoted	Unit Cost	Ext Cost
1	12	Resistor, Balance, 10k, 25W	Y	3.00	36.00
2	24	Capacitor, 8200uF, 450Vdc	Y	47.00	1,128.00
3	6	IGBT, 1200A, 2500V	Y	510.00	3,060.00
4	1	Gate Drive Board, Hex	Y	325.00	325.00
5	1	Assy, Laminated Bus	Y	1,000.00	1,000.00
6	1	Heatsink	Y	1,176.00	1,176.00
7	1	Cooling Fan	Y	450.00	450.00
8	1	Fiber Optic Harness	Y	118.00	118.00
		TOTAL:			**7,293.00**

3.2.6 Line Filter for 3.0-MW LV Turbine

The line filter for the 3.0-MW converter is shown below and consists of an inductive and capacitive element. The padmount transformer leakage inductance helps to form a T-section low-pass filter.

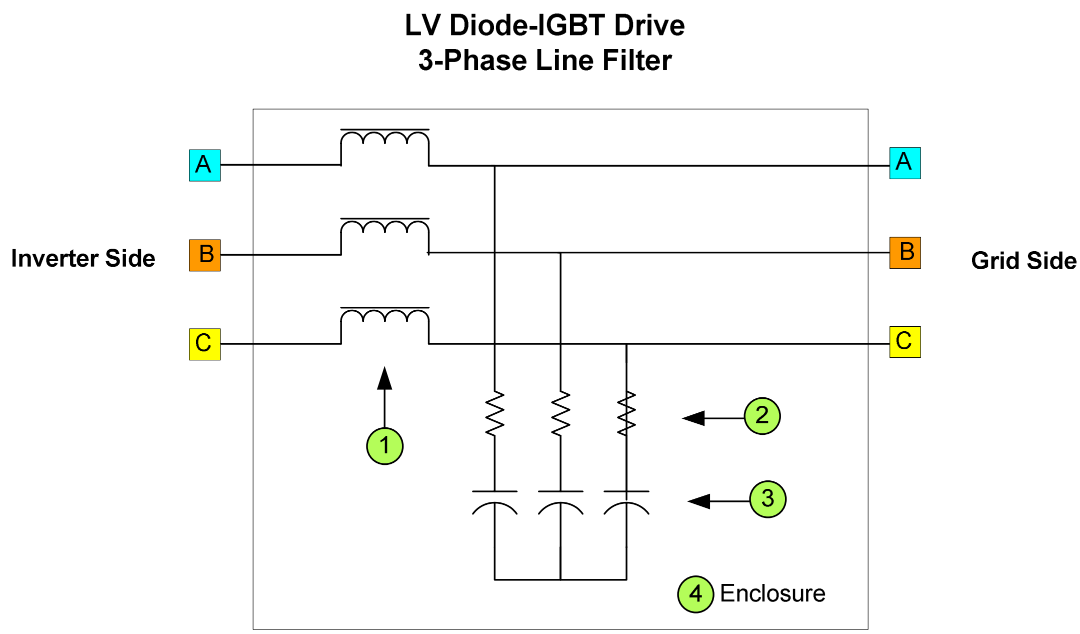


Figure 3-5 Line filter schematic, 3.0-MW LV turbine

Table 3-5 Line filter costing, 3.0-MW LV turbine

LV 750 kVA Line Filter BOM

Item #	Qty	Description	Quoted	Unit Cost	Ext Cost
1	1	Reactor, PWM, 600uH, 3 Phase	Y	5,500.00	5,500.00
2	3	Resistor, Stainless, 3 phase, 0.1 Ω/Phase	Y	33.00	99.00
3	1	Capacitor, 20.8 kVAR, 3 Phase, 575V	Y	141.00	141.00
4	1	Enclosure	Y	600.00	600.00
		TOTAL:			**6,340.00**

3.2.7 Converter Subpanel for 3.0-MW LV Turbine

The subpanel is made up of many small components used in the converter. The subpanel is a convenient approach to mounting and managing the various components.

Table 3-6 Converter subpanel costing, 3.0-MW LV turbine

LV 750 kVA Sub-Panel BOM

Item #	Qty	Description	Quoted	Unit Cost	Ext Cost
1	1	Fab, Panel, Power Distribution	Y	50.00	50.00
2	1	Switch, Disconnect, 80A, 600V, 2p	Y	180.00	180.00
3	2	Circuit Breaker, 30A, 600V, 3-P	Y	120.80	241.60
4	3	Fuse, 30A, 600V	Y	5.00	15.00
5	3	Fuseblock, 100A, 600V	Y	5.00	15.00
6	2	Capacitor, Electrolytic, 300uF, 250V	Y	15.00	30.00
7	1	Assy, Harness, Main	Y	300.00	300.00
8	1	Circuit Breaker, 20A, 600V	Y	93.80	93.80
9	1	Circuit Breaker, 2A, 600V	Y	70.00	70.00
10	4	SSR, 12A, 200Vdc, MOSFET OUT	Y	17.00	68.00
11	250	350 MCM 2000V Cable	Y	2.50	625.00
12	1	Transformer, Control, 4kVA 1ph	Y	350.00	350.00
		TOTAL:			**2,038.40**

3.2.8 Passive Rectifier for 3.0-MW LV Turbine

The rectifier used in the LV system is a simple passive six-element design (Figure 2.6). The six rectifiers are mounted on a heatsink, and a cooling fan is used to manage the relatively small losses associated with this subassembly.

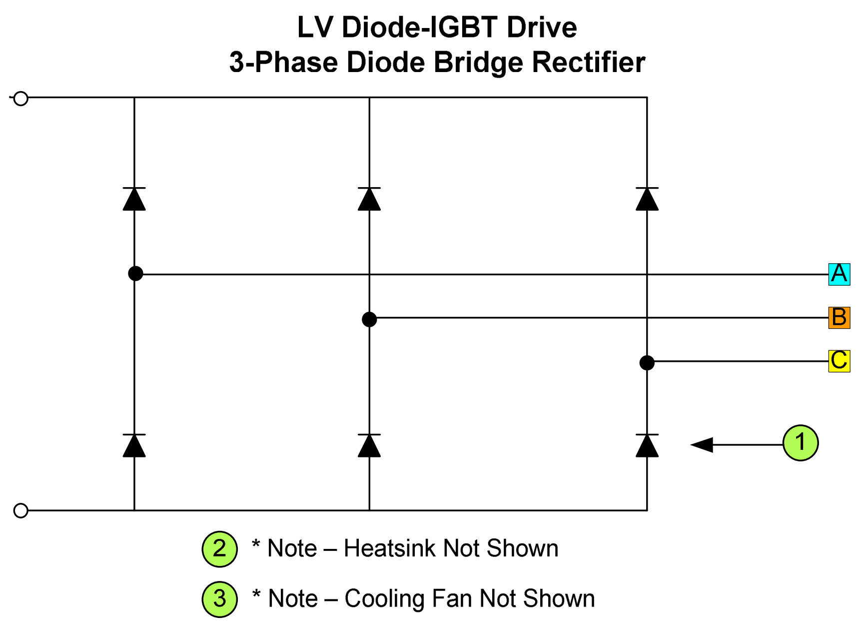


Figure 3-6 Passive rectifier, 3.0-MW LV turbine

Table 3-7 Passive rectifier costing, 3.0-MW LV turbine

LV 750 kVA Diode Bridge BOM

Item #	Qty	Description	Quoted	Unit Cost	Ext Cost
1	6	Diode, 1200A, 2400V, Fast Recovery	Y	238.00	1,428.00
2	1	Heatsink, Clamps, Terminations	Y	710.00	710.00
3	1	Cooling Fan and Switchgear	Y	325.00	325.00
		TOTAL:			**2,463.00**

3.3 Electrical System BOM for 5.0-MW LV Turbine

Table 3-8 below lists the electrical system BOM for the 5.0-MW LV turbine. The material cost totalized at the bottom of the table will be compared with the MV design in the COE models of Section 5.

Table 3-8 5.0-MW LV electrical system BOM

#	Item	Description	Cost
1	Generator	5.0 MW, 105 Deg. C rise, 6 pole, open drip-proof, flange mounted, 33% reactance, wye connected, form wound, 97% F.L. efficiency	$ 164,000
2	Tower Pendant Cables	8354 ft. of 2kV, 90 deg C., 300 MCM, normal stranding	$ 48,681
3	Tower Pendant Cables (festooning)	1474 ft., 2 kV, high stranded, 313 MCM DLO	$ 9,546
4	LV Inverter	Voltage source inverter per attached included BOM's	$ 265,128
5	Transformer and Switchgear	5MVA, Oil filled padmount, outdoor rated, 34.5 kV primary, 575 V wye secondary	$ 45,911
		Total Cost	$ 533,266

3.3.1 Converter System for 5.0-MW LV Turbine

The 5.0-MW LV variable-speed converter system consists of a passive rectifier and IGBT inverter system. As discussed earlier, a limit of 750 kW represents the maximum cost-effective approach to LV converters. In the 5.0-MW system, eight x 625 kW, operating in parallel, are used. This configuration is shown in the simplified schematic of Figure 3-7. Note that there are now two control boards, each controlling four converters. While it is preferable to use one control board, the control of eight converters is beyond the I/O capability and processing power, which could be expected. The two control board costs need to be added to subsequent BOMs as these are not included at any assembly or subassembly level below. This cost is $2657. Figures of line filter and switchgear are not included; these are the same as discussed in the 3.0-MW section of this report. The adjusted costing, however, is provided in the sections below.

3.3.2 Converter System Diagram for 5.0-MW LV Turbine

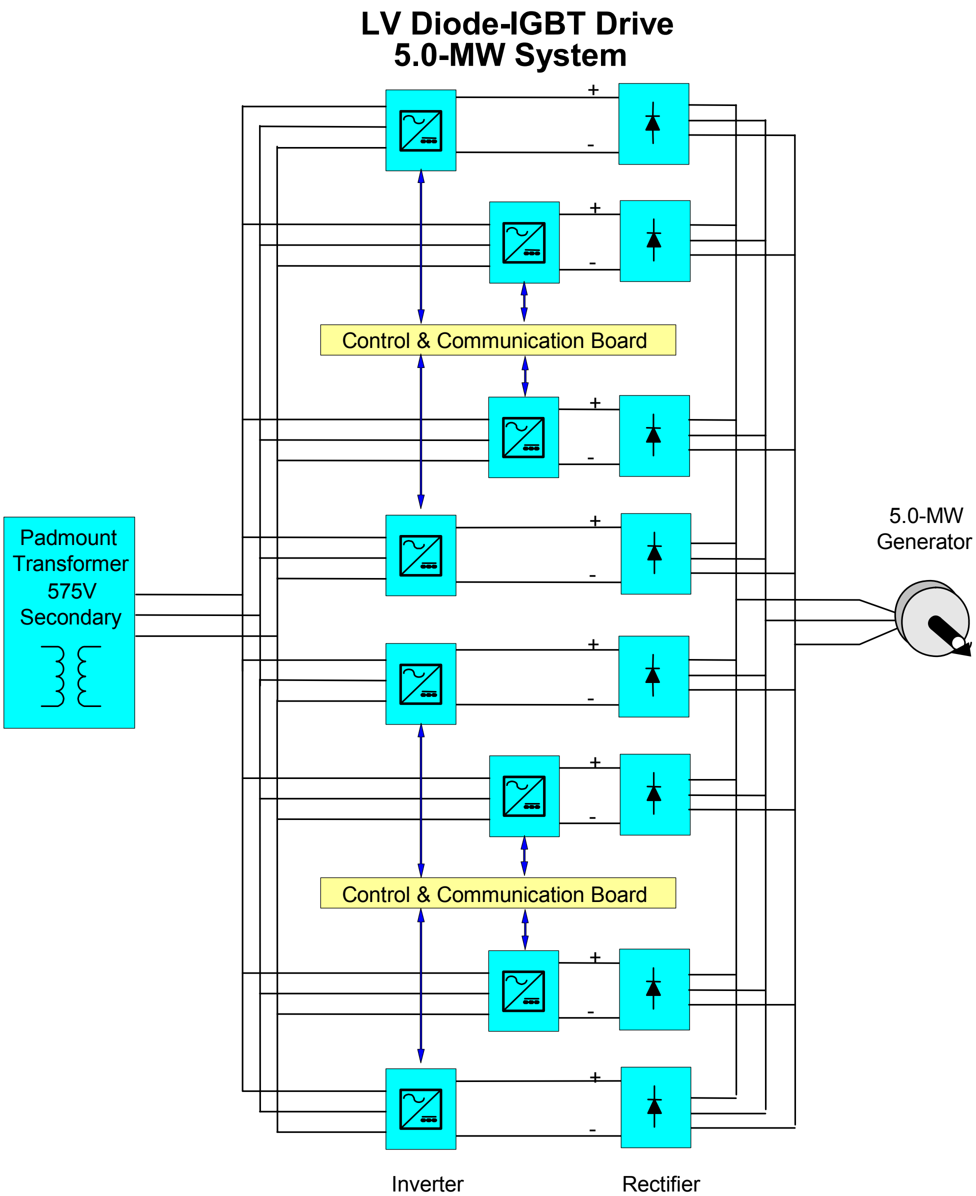


Figure 3-7 Converter system diagram, 5.0-MW LV turbine

3.3.3 Converter Pricing Spreadsheet for 5.0-MW LV Turbine

The table below shows the buildup of costing for the 5.0-MW converter system.

Table 3-9 Converter pricing spreadsheet, 5.0-MW LV turbine

5.0-MW LV Synchronous Machine Drive			
Direct Variable Materials[1]	$ 183,267.08	$ 183,267.08	$ 183,267.08
Direct Variable Labor[2]	$ 13,742.86	$ 13,742.86	$ 13,742.86
Direct Fixed Costs[3]	$ 1,836.00	$ 1,836.00	$ 1,836.00
Total Direct Costs	$ 198,845.93	$ 198,845.93	$ 198,845.93
Gross Margin[4]	20%	25%	30%
Sales Price	$ 248,557.42	$ 265,127.91	$ 284,065.62

(1) Annual production = 250 Turbines
(2) Includes 3% freight in
(3) Assumes 70% utilization and 30% fringe benefits
(4) Includes $120k rent, $200k capital equip, $54k utility and $85k supervision (annual cost)
(5) Gross Margin = (Sales Price - Direct Cost)/Sales Price

3.3.4 Converter Material Breakdown and BOM for 5.0-MW LV Turbine

The material costing of the converter is broken down further as shown below. Note that the schematics and figures associated with each BOM are not included in this section as they are identical to those corresponding figures in the 3.0-MW converter section. For example, the inverter topology, the line filter, etc. are schematically the same as in the 3.0-MW system, but the component values are optimized in accordance with the reduced rating of 625 kW. These different components can be identified in the respective BOMs below.

Table 3-10 5.0-MW LV Converter BOM

LV 625 kVA Converter BOM

Item #	Qty	Description	Quoted	Unit Cost	Ext Cost
1	1	Circuit Breaker, 1000A, 600VAC, 3-P, Line	Y	1,200.00	1,200.00
2	1	Fuse, 700A, 600VAC, 3-Pole	Y	120.00	120.00
3	1	Contactor, 700A, 600VAC, 3-Pole, Line	Y	1,200.00	1,200.00
4	1	Line Filter, 3 Phase	N/A	5,840.00	5,840.00
5	1	Assy, IGBT Matrix, 3-Phase, Line	N/A	7,293.00	7,293.00
6	1	Diode Bridge	N/A	2,463.00	2,463.00
7	1	Sub Panel	N/A	1,913.40	1,913.40
8	1	Enclosure	Y	1,100.00	1,100.00
9	4	Current Transducers, Line	Y	195.00	780.00
		TOTAL:			**21,909.40**

3.3.5 Line Matrix 5.0-MW LV Turbine

Costing for the 5.0-MW LV turbine line matrix including all power semiconductors and DC link capacitors and other equipment is provided below.

Table 3-11 Line matrix costing, 5.0-MW LV turbine

LV 625 kVA Line Matrix BOM

Item #	Qty	Description	Quoted	Unit Cost	Ext Cost
1	12	Resistor, Balance, 10k, 25W	Y	3.00	36.00
2	24	Capacitor, 8200uF, 450Vdc	Y	47.00	1,128.00
3	6	IGBT, 1200A, 2500V	Y	510.00	3,060.00
4	1	Gate Drive Board, Hex	Y	325.00	325.00
5	1	Assy, Laminated Bus	Y	1,000.00	1,000.00
6	1	Heatsink	Y	1,176.00	1,176.00
7	1	Cooling Fan	Y	450.00	450.00
8	1	Fiber Optic Harness	Y	118.00	118.00
		TOTAL:			**7,293.00**

3.3.6 Line Filter for 5.0-MW LV Turbine

The line filter for the 5.0-MW turbine is described and costed below.

Table 3-12 Line filter BOM, 5.0-MW LV turbine

LV 625 kVA Line Filter BOM

Item #	Qty	Description	Quoted	Unit Cost	Ext Cost
1	1	Reactor, PWM, 800uH, 3 Phase	Y	5,000.00	5,000.00
2	3	Resistor, Stainless, 3 phase, 0.1 Ω/Phase	Y	33.00	99.00
3	1	Capacitor, 20.8 kVAR, 3 Phase, 575V	Y	141.00	141.00
4	1	Enclosure	Y	600.00	600.00
		TOTAL:			**5,840.00**

3.3.7 Converter Subpanel for 5.0-MW LV Turbine

The 5.0-MW turbine subpanel has the same components mounted on it as in the 3.0-MW case.

Table 3-13 Converter subpanel costing, 5.0-MW LV turbine

LV 625 kVA Sub-Panel BOM

Item #	Qty	Description	Quoted	Unit Cost	Ext Cost
1	1	Fab, Panel, Power Distribution	Y	50.00	50.00
2	1	Switch, Disconnect, 80A, 600V, 2p	Y	180.00	180.00
3	2	Circuit Breaker, 30A, 600V, 3-P	Y	120.80	241.60
4	3	Fuse, 30A, 600V	Y	5.00	15.00
5	3	Fuseblock, 100A, 600V	Y	5.00	15.00
6	2	Capacitor, Electrolytic, 300uF, 250V	Y	15.00	30.00
7	1	Assy, Harness, Main	Y	300.00	300.00
8	1	Circuit Breaker, 20A, 600V	Y	93.80	93.80
9	1	Circuit Breaker, 2A, 600V	Y	70.00	70.00
10	4	SSR, 12A, 200Vdc, MOSFET OUT	Y	17.00	68.00
11	250	262 MCM 2000V Cable	Y	2.00	500.00
12	1	Transformer, Control, 4kVA 1ph	Y	350.00	350.00
		TOTAL:			**1,913.40**

3.3.8 Passive Rectifier for 5.0-MW LV Turbine

The rectifier for the 5.0-MW LV turbine is identical to the 3.0-MW design and is costed below.

Table 3-14 Passive rectifier costing, 5.0-MW LV turbine

LV 625 kVA Diode Bridge Rectifier BOM

Item #	Qty	Description	Quoted	Unit Cost	Ext Cost
1	6	Diode, 1200A, 2400V, Fast Recovery	Y	238.00	1,428.00
2	1	Heatsink, Clamps, Terminations	Y	710.00	710.00
3	1	Cooling Fan and Switchgear	Y	325.00	325.00
		TOTAL:			**2,463.00**

3.4 Electrical System BOM for 7.5-MW LV Turbine

The 7.5-MW LV variable-speed converter system consists of a passive rectifier and IGBT inverter. Just as in the 3.0-MW case study, the 7.5-MW turbine uses a highly paralleled 750-kW converter module structure to achieve the required 7.5 MW. In this system, ten 750-kW converters are used to achieve the turbine's rating. This configuration is shown in the simplified schematic of Figure 3-8. Note that three control boards are now used on the turbine, two control boards controlling four converters each and a third control board controlling only two converters. The cost for the three control boards is $3985, which must be added to material costs. The addition of multiple control boards complicates communication with turbine control systems. It is necessary for the boards to flag each other in the event of a fault condition. Matrix, line filter, subpanel, and switchgear are not included as figures or BOMs in this section because they are identical to the assemblies mentioned in the 3.0-MW discussion.

Table 3-15 7.5-MW LV electrical system BOM

#	Item	Description	Cost
1	Generator	7.5 MW, 105 Deg. C rise, 6 pole, open drip-proof, flange mounted, 33% reactance, wye connected, form wound, 97% F.L. efficiency	$ 241,000
2	Tower Pendant Cables	12,846 ft. of 2kV, 90 deg C., 300 MCM, normal stranding	$ 74,857
3	Tower Pendant Cables (festooning)	2267 ft., 2 kV, high stranded, 313 MCM DLO	$ 14,677
4	LV Inverter	Voltage source inverter per attached included BOM's	$ 345,858
5	Transformer and Switchgear	5MVA, Oil filled padmount, outdoor rated, 34.5 kV primary, 575 V wye secondary	$ 62,445
		Total Cost	$ 738,837

3.4.1 Converter System Diagram for 7.5-MW LV Turbine

The converter system diagram for the 7.5-MW LV turbine is shown in Figure 3.8.

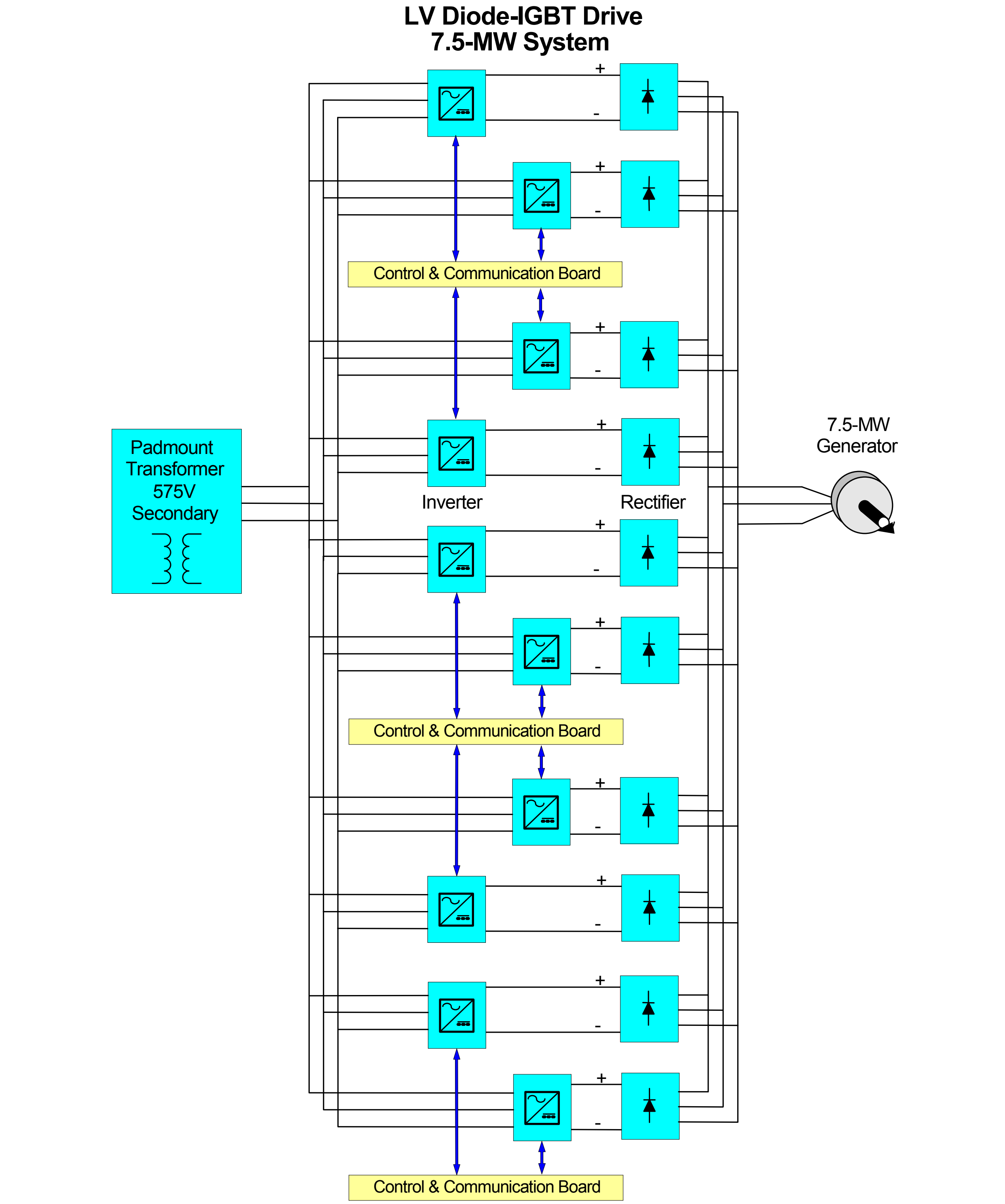


Figure 3-8 Converter system diagram, 7.5-MW LV turbine

3.4.2 Converter Pricing Spreadsheet for 7.5-MW LV Turbine

Pricing for the highly paralleled 7.5-MW LV turbine is shown below. The costing includes three control boards for a total cost adder of $3985.

Table 3-16 Converter pricing spreadsheet, 7.5-MW LV turbine

7.5-MW LV Synchronous Machine Drive			
Direct Variable Materials[1]	$ 240,324.75	$ 240,324.75	$ 240,324.75
Direct Variable Labor[2]	$ 17,178.57	$ 17,178.57	$ 17,178.57
Direct Fixed Costs[3]	$ 1,890.00	$ 1,890.00	$ 1,890.00
Total Direct Costs	$ 259,393.32	$ 259,393.32	$ 259,393.32
Gross Margin[4]	20%	25%	30%
Sales Price	$ 324,241.65	$ 345,857.76	$ 370,561.89

(1) Annual production = 250 Turbines
(2) Includes 3% freight in
(3) Assumes 70% utilization and 30% fringe benefits
(4) Includes $120k rent, $200k capital equip, $67.5k utility and $85k supervision (annual cost)
(5) Gross Margin = (Sales Price - Direct Cost)/Sales Price

4 Electrical System Bill of Material – MV Voltage-Source Inverter Topology

As in Section 3, this section details the electrical system BOM for the 3.0-, 5.0-, and 7.5-MW turbines. In this case, however, a North American MV electrical system is assumed instead of the conventional 575-V configuration. The voltages used are 2,400V at 3.0 MW, 4,160V at 5.0 MW, and 6,900V at 7.5 MW. These voltages were selected to keep the AC line currents at about 700 amps for all three turbines, which costing efforts demonstrate provide the most cost-effective MV equipment.

Building on the baseline electrical system, in this section the MV converters are priced out in detail. The converters for the 5.0- and 7.5-MW turbines share a three-level, neutral-point clamp, voltage-source inverter topology. This topology is now well understood [1], [2] and has numerous advantages at higher voltages. The 3.0-MW turbine converter uses a 6-element voltage-source inverter using 6.6-kV power semiconductors.

In addition to the changes in the inverter section, a boost converter is added in the DC link between the generator rectifier and the inverter. The chopper allows a wide DC-bus operating range, as provided in the LV case, without exceeding the voltage limit of available power semiconductors. The chopper has another advantage in that it extends the operating speed range of the generator, and this wider range corresponds to about a 0.3% increase in the energy capture of the MV turbine. However, this is offset by a slightly lower efficiency due to the boost circuit. A detailed analysis of the net gains or losses due to these effects is not performed in this study. The converter topologies are detailed below.

4.1 Section Organization

This section is arranged to parallel the development of the LV cases in Section 3. Specifically, Sections 4.2, 4.3, and 4.4 detail costs and materials for the 3.0-, 5.0-, and 7.5-MW electrical systems, respectively. The subsections then follow the same order as was used in Section 2 costing and pricing.

4.2 Electrical System BOM for 3.0-MW MV Turbine

Table 4-1 lists the electrical system BOM for the 3.0-MW MV turbine. The material cost totalized at the bottom of the table will be compared with the LV design in the COE models of Section 5.

Table 4-1 3.0-MW MV electrical system BOM

#	Item	Description	Cost
1	Generator	3.0 MW, 105 Deg. C rise, 6 pole, open drip-proof, flange mounted, 33% reactance, wye connected, form wound, 97% F.L. efficiency	$ 114,000
2	Tower Pendant Cables	812 ft. of 5kV shielded, 90 deg C., 600 MCM,normal stranding	$ 7,578
3	Tower Pendant Cables (festooning)	143 ft., 5 kV, high stranded, 600 MCM DLO	$ 1,471
4	LV Inverter	Voltage source inverter per attached included BOM's	$ 110,494
5	Transformer and Switchgear	3MVA, Oil filled padmount, outdoor rated, 34.5 kV primary, 2400 V wye secondary	$ 34,212
		Total Cost	$ 267,755

4.2.1 Converter System for 3.0-MW MV Turbine

The 3.0-MW MV variable-speed converter system consists of a passive rectifier, generator, boost chopper, and three-level Integrated Gate-Commutated Thyristor (IGCT) inverter system. In contrast to the highly paralleled architecture of the LV system, the MV electrical system consists of a single generator output and a single converter system.

4.2.2 Converter System Schematic and Pricing for 3.0-MW MV Turbine

Pricing for the 3.0-MW MV turbine is provided in the spreadsheet below. The structure of the 3.0-MW machine includes material cost for a control board in the fundamental converter in the next section, so no control board cost adder is required (unlike the LV case).

Table 4-2 Pricing Spreadsheet for 3.0-MW MV Turbine

3.0-MW MV Voltage Source Synchronous Machine Drive			
Direct Variable Materials (1)	$ 79,146.23	$ 79,146.23	$ 79,146.23
Direct Variable Labor (2)	$ 1,996.43	$ 1,996.43	$ 1,996.43
Direct Fixed Costs (3)	$ 1,728.00	$ 1,728.00	$ 1,728.00
Total Direct Costs	$ 82,870.66	$ 82,870.66	$ 82,870.66
Gross Margin (4)	20%	25%	30%
Sales Price	$ 103,588.32	$ 110,494.21	$ 118,386.66

(1) Annual production = 250 Turbines
(2) Includes 3% freight in
(3) Assumes 70% utilization and 30% fringe benefits
(4) Includes $120k rent, $200k capital equip, $27k utility and $85k supervision (annual costs)
(5) Gross Margin = (Sales Price - Direct Cost)/Sales Price

4.2.3 Converter System Material Breakdown and BOM for 3.0-MW MV Turbine

A basic diagram and material cost of the MV converter main assemblies are shown below, with subassembly details shown in the subsequent four sections. As in the previous section, costs for components and subassemblies are based on vendor quotations or project team estimates, as identified in the Quoted column.

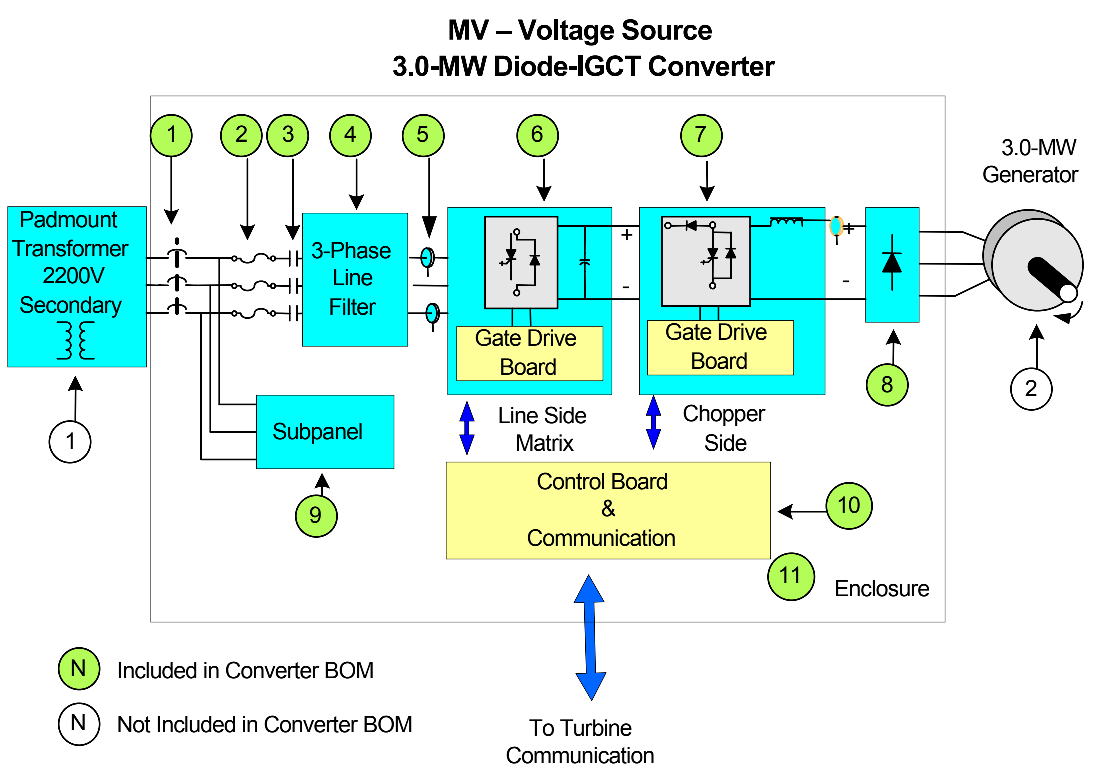


Figure 4-1 3.0-MW MV converter diagram

Table 4-3 3.0-MW MV converter BOM

3.0-MW MV Diode-IGCT Converter BOM

Item #	Qty	Description	Quoted	Unit Cost	Ext Cost
1	1	Circuit Breaker, 800A, 2400VAC, 3-P, Line	Y	3,106.00	3,106.00
2	1	Fuse, 800A, 2400VAC, 3-Pole	Y	2,798.00	2,798.00
3	1	Contactor, 800A, 2400VAC, 3-Pole, Line	Y	2,715.00	2,715.00
4	1	Line Filter, 3 Phase	N/A	28,150.00	28,150.00
5	3	Current Transducers 900A	Y	93.20	279.60
6	1	Assy, IGCT Matrix, 3-Phase, Line	N/A	17,074.00	17,074.00
7	1	Assy, Diode-IGCT Chopper	N/A	12,254.00	12,254.00
8	1	Diode Bridge	N/A	4,236.00	4,236.00
9	1	Sub Panel	N/A	2,878.40	2,878.40
10	1	Control Board	Y	1,350.00	1,350.00
11	1	Enclosure	Y	2,000.00	2,000.00
		TOTAL:			76,841.00

4.2.4 Line Matrix for 3.0-MW MV Turbine

The line side inverter matrix for the 3.0-MW converter is shown below. The matrix uses asymmetrical IGCT devices rated at 6.6 kV. Costing for the line side inverter matrix is shown below the filter.

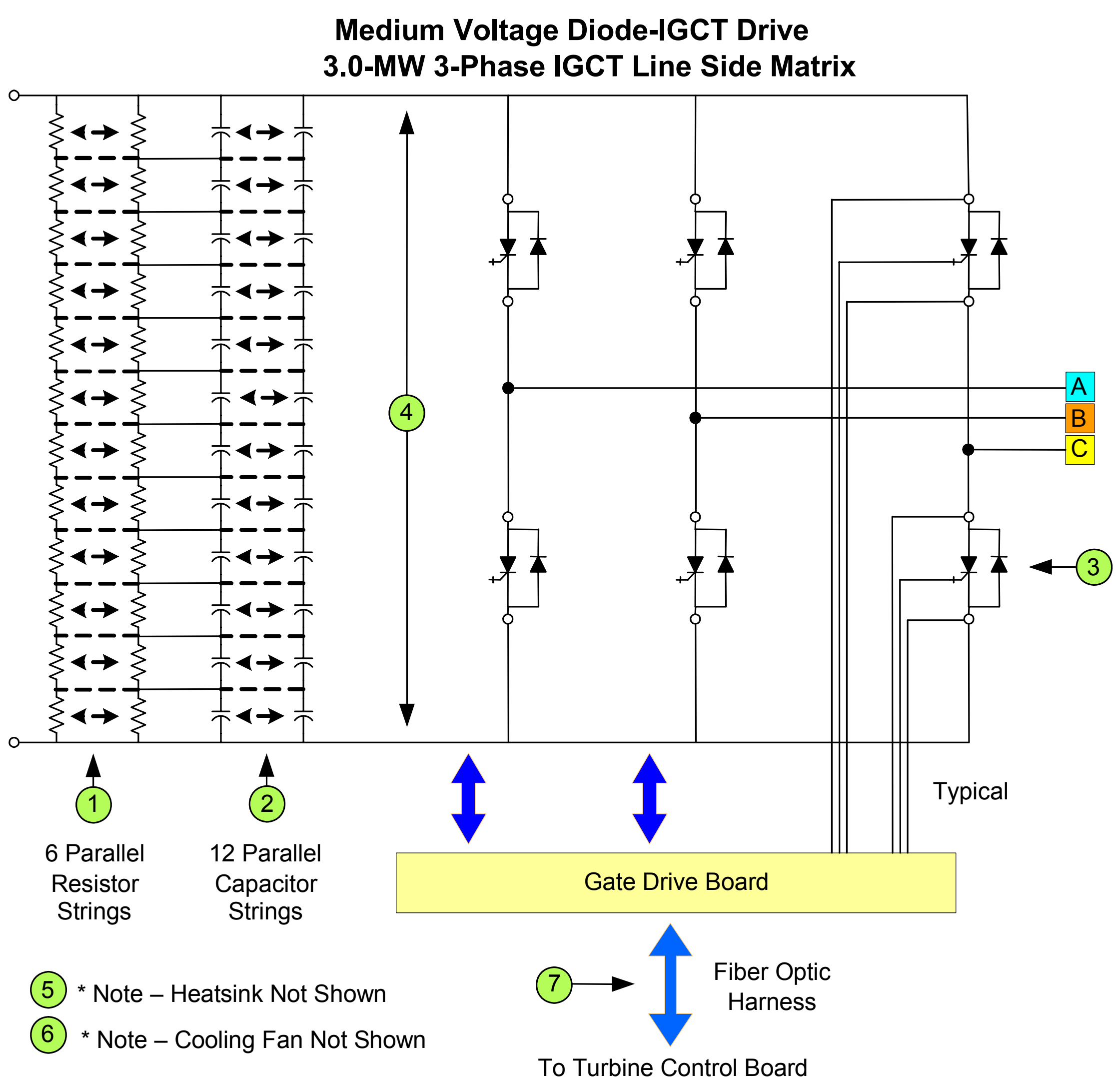


Figure 4-2 Line matrix schematic, 3.0-MW MV turbine

Table 4-4 Line matrix costing, 3.0-MW MV turbine

3.0-MW MV Diode -IGCT Matrix BOM

Item #	Qty	Description	Quoted	Unit Cost	Ext Cost
1	72	Resistor, Balance, 10k, 25W	Y	3.00	216.00
2	144	Capacitor, 8200uF, 450Vdc	Y	47.00	6,768.00
3	6	IGCT, 1200A, 6.6kV	Y	962.00	5,772.00
4	1	Assy, Laminated Bus	Y	1,200.00	1,200.00
5	1	Heatsink	Y	2,500.00	2,500.00
6	1	Cooling Fan	Y	500.00	500.00
7	1	Fiber Optic Harness	Y	118.00	118.00
		TOTAL:			17,074.00

4.2.5 Chopper for 3.0-MW MV Turbine

As mentioned above, the MV, voltage-source inverter uses a chopper to regulate the DC bus. Recall that bus voltage regulation is intentionally moved to the generator side for ride-through requirement purposes. The chopper also extends the speed range of the MV design.

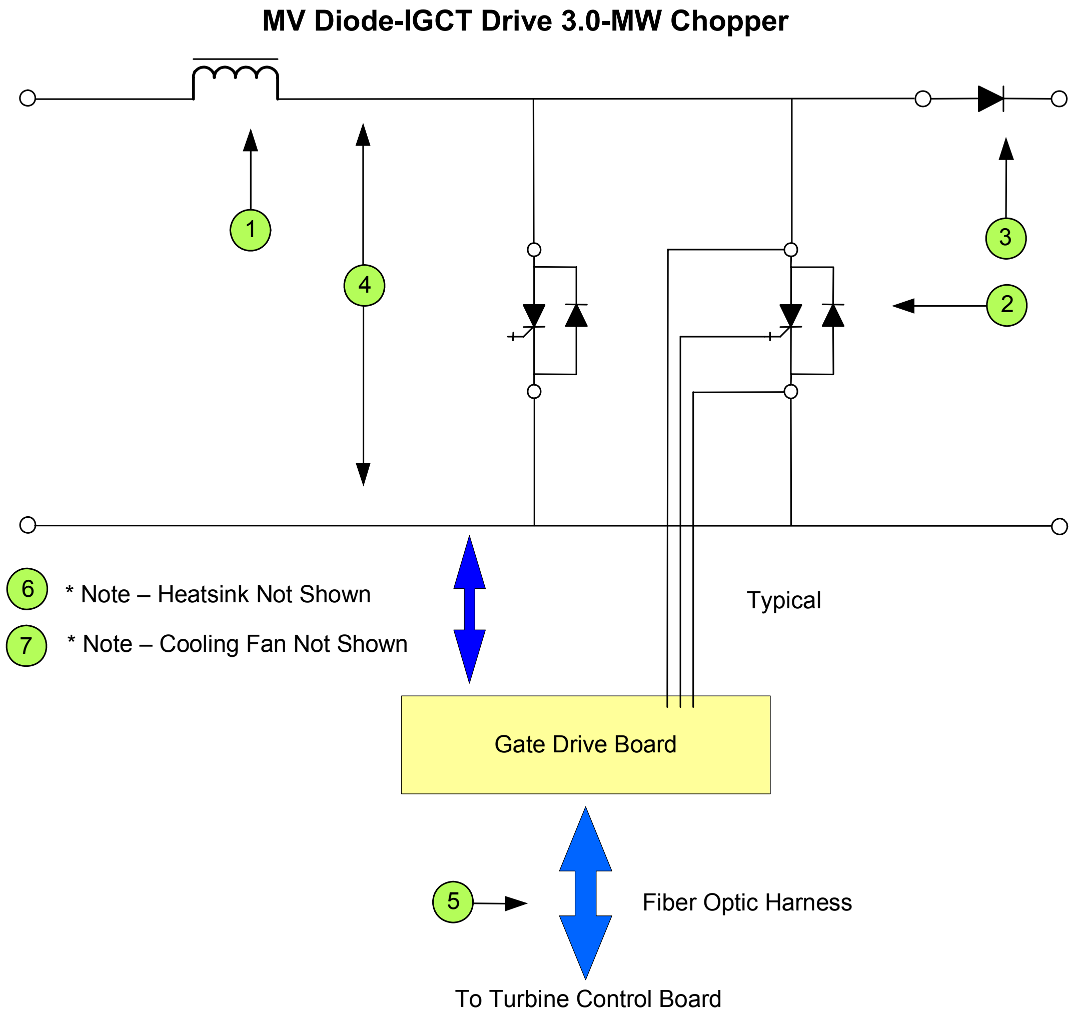


Figure 4-3 3.0-MW MV chopper diagram

Table 4-5 3.0-MW MV chopper BOM

3.0-MW MV Diode-IGCT Chopper BOM

Item #	Qty	Description	Quoted	Unit Cost	Ext Cost
1	1	Inductor, Chopper, 1mH 900Adc	Y	5,600.00	5,600.00
2	2	IGCT, 1200A, 6.6kV	Y	962.00	1,924.00
3	1	Diode, Chopper, 1200A, 6.6kV	Y	412.00	412.00
4	1	Assy, Laminated Bus	Y	1,200.00	1,200.00
5	1	Fiber Optic Harness	Y	118.00	118.00
6	1	Heatsink	Y	2,500.00	2,500.00
7	1	Cooling Fan	Y	500.00	500.00
		TOTAL:			12,254.00

4.2.6 *Line Filter for 3.0-MW MV Turbine*

The line filter for the 3.0-MW inverter is similar to that used in the LV case. The filter is diagrammed and costed below.

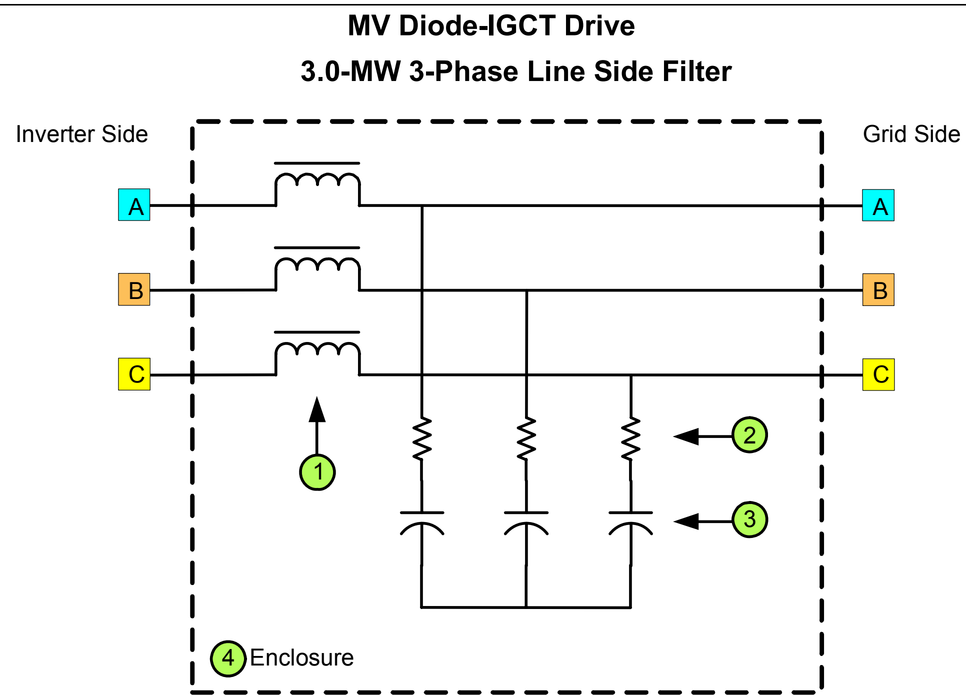


Figure 4-4 Line filter schematic, 3.0-MW MV turbine

Table 4-6 Line filter costing, 3.0-MW MV turbine

3.0-MW MV Diode-IGCT Filter BOM

Item #	Qty	Description	Quoted	Unit Cost	Ext Cost
1	1	Reactor, PWM, 6mH, 700A, 3 Phase, 2400V	Y	24,000.00	24,000.00
2	3	Resistor, Stainless, 3 phase, 0.1 Ω/Phase	Y	500.00	1,500.00
3	1	Capacitor, 100 kVAR, 3 Phase, 4160V	Y	1,850.00	1,850.00
4	1	Enclosure	Y	800.00	800.00
		TOTAL:			28,150.00

4.2.7 *Converter Subpanel for 3.0-MW MV Turbine*

The subpanel design in the MV case is identical to that used in the LV case. The subpanel is costed below.

Table 4-7 Converter subpanel costing, 3.0-MW MV turbine

3.0-MW MV Diode-IGCT Subpanel BOM

Item #	Qty	Description	Quoted	Unit Cost	Ext Cost
1	1	Xfmr, 3 phase Isolation, 2400:240, 5kVA	Y	500.00	500.00
2	1	Fab, Panel, Power Distribution	Y	50.00	50.00
3	1	Switch, Disconnect, 80A, 600V, 2p	Y	180.00	180.00
4	2	Circuit Breaker, 30A, 600V, 3-P	Y	120.80	241.60
5	3	Fuse, 30A, 600V	Y	5.00	15.00
6	3	Fuseblock, 100A, 600V	Y	5.00	15.00
7	2	Capacitor, Electrolytic, 300uF, 250V	Y	15.00	30.00
8	1	Assy, Harness, Main	Y	300.00	300.00
9	1	Circuit Breaker, 20A, 600V	Y	93.80	93.80
10	1	Circuit Breaker, 2A, 600V	Y	70.00	70.00
11	4	SSR, 12A, 200Vdc, MOSFET OUT	Y	17.00	68.00
12	250	350 MCM 2000V Cable	Y	3.86	965.00
13	1	Transformer, Control, 4kVA 1ph	Y	350.00	350.00
		TOTAL:			2,878.40

4.2.8 Passive Rectifier for 3.0-MW MV Turbine

The passive rectifier for the MV converter is similar to the LV design. It uses a heatsink and fan assembly to remove the rather small losses given off by the six elements.

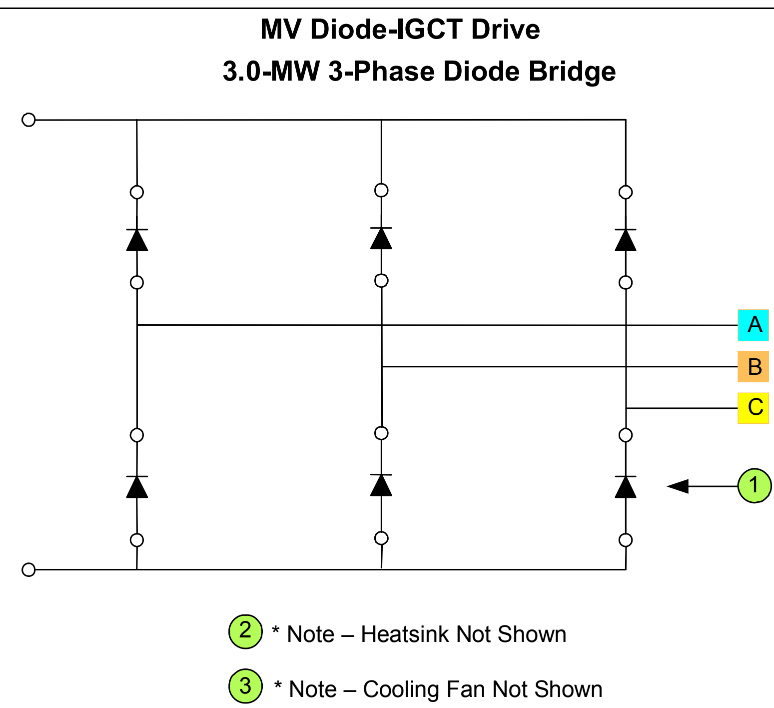


Figure 4-5 Passive rectifier, 3.0-MW MV turbine

Table 4-8 Passive rectifier costing, 3.0-MW MV turbine

3.0-MW MV Diode-IGCT Diode Bridge Rectifier BOM

Item #	Qty	Description	Quoted	Unit Cost	Ext Cost
1	6	Diode, 1200A, 6.6kV, Fast Recovery	Y	418.00	2,508.00
2	1	Heatsink, Clamps, Terminations	Y	1,372.00	1,372.00
3	1	Cooling Fan and Switchgear	Y	356.00	356.00
		TOTAL:			4,236.00

4.3 Electrical System BOM for 5.0-MW MV Turbine

Table 4-9 lists the electrical system BOM for the 5.0-MW MV voltage-source inverter turbine. The material cost totalized at the bottom of the table will be compared with the MV design in the COE models of Section 5.

Table 4-9 5.0-MW MV Electrical System BOM

#	Item	Description	Cost
1	Generator	5.0 MW, 105 Deg. C rise, 6 pole, open drip-proof, flange mounted, 33% reactance, wye connected, form wound, 97% F.L. efficiency	$ 164,000
2	Tower Pendant Cables	8354 ft. of 5kV shielded, 90 deg C., 500 MCM, normal stranding	$ 7,795
3	Tower Pendant Cables (festooning)	184 ft., 5 kV, high stranded, 500 MCM DLO	$ 1,513
4	LV Inverter	Voltage source inverter per attached included BOM's	$ 146,167
5	Transformer and Switchgear	5MVA, Oil filled padmount, outdoor rated, 34.5 kV primary, 4160 V wye secondary	$ 41,354
		Total Cost	$ 360,829

4.3.1 Converter System for 5.0-MW MV Turbine

The 5.0-MW MV variable-speed converter system consists of a passive rectifier, generator, boost chopper, and three-level IGCT inverter system. In contrast to the highly paralleled architecture of the LV system, the MV electrical system consists of a single generator output and a single converter system.

4.3.2 Converter System Schematic and Pricing for 5.0-MW MV Turbine

The pricing for the 5.0-MW converter is as follows.

Table 4-10 Converter system pricing spreadsheet, 5.0-MW MV turbine

5.0-MW Permanent Magnet Drive						
Direct Variable Materials (1)	$	105,689.74	$	105,689.74	$	105,689.74
Direct Variable Labor (2)	$	2,135.71	$	2,135.71	$	2,135.71
Direct Fixed Costs (3)	$	1,800.00	$	1,800.00	$	1,800.00
Total Direct Costs	$	109,625.46	$	109,625.46	$	109,625.46
Gross Margin (4)		20%		25%		30%
Sales Price	$	137,031.82	$	146,167.28	$	156,607.79

(1) Annual production = 250 Turbines
(2) Includes 3% freight in
(3) Assumes 70% utilization and 30% fringe benefits
(4) Includes $120k rent, $200k capital equip, $45k utility and $85k supervision (annual cost)
(5) Gross Margin = (Sales Price - Direct Cost)/Sales Price

4.3.3 Converter Material Breakdown and BOM for 5.0-MW MV Turbine

The material costing of the converter is broken down further as shown below.

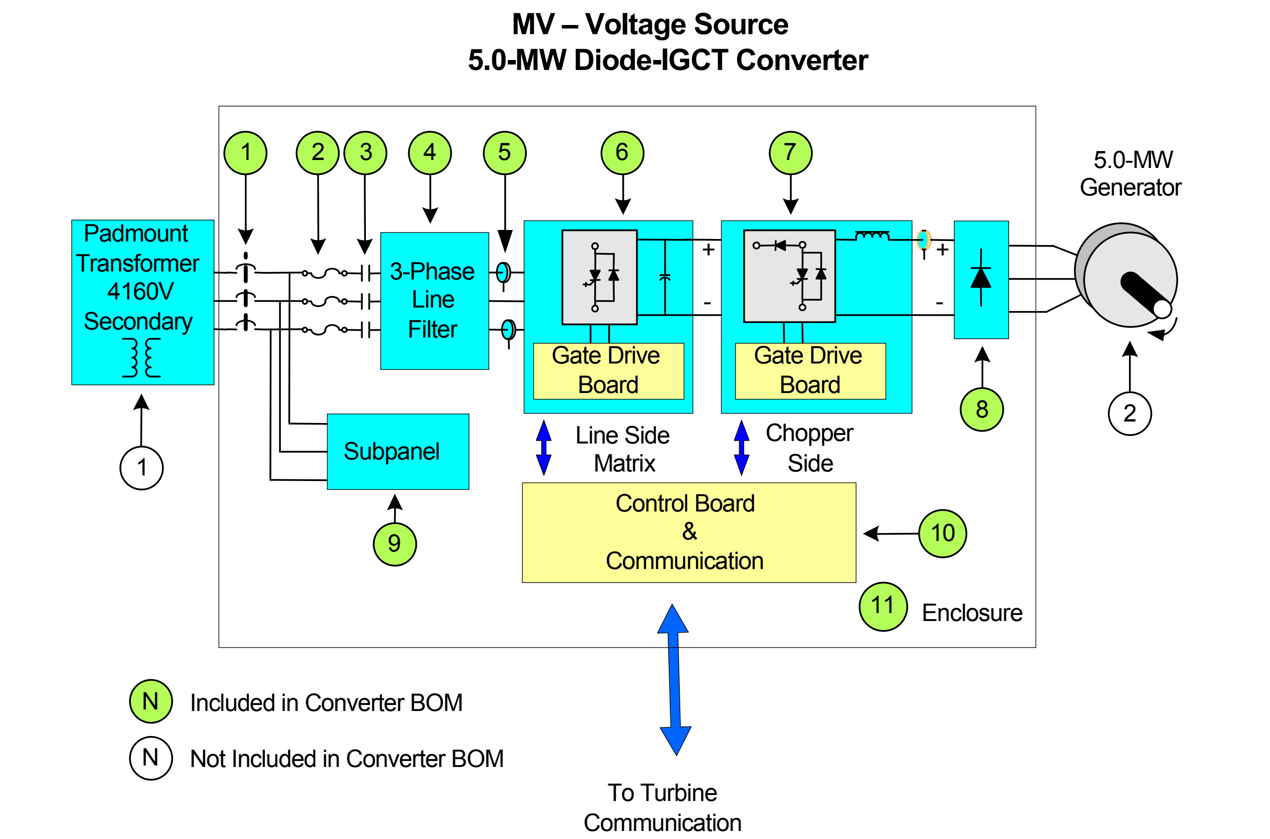


Figure 4-6 5.0-MW MV converter diagram

Table 4-11 5.0-MW MV converter BOM

5.0-MW MV Diode-IGCT Converter BOM

Item #	Qty	Description	Quoted	Unit Cost	Ext Cost
1	1	Circuit Breaker, 800A, 5kVAC, 3-Pole, Line	Y	3,106.00	3,106.00
2	1	Fuse, 800A, 5kVAC, 3-Pole	Y	2,798.00	2,798.00
3	1	Contactor, 800A, 5kVAC, 3-Pole, Line	Y	2,715.00	2,715.00
4	1	Line Filter, 3 Phase	N/A	28,150.00	28,150.00
5	3	Current Transducers 900A	Y	450.00	1,350.00
6	1	Assy, IGCT Matrix, 3-Phase, Line	N/A	32,602.00	32,602.00
7	1	Assy, Diode-IGCT Chopper	N/A	18,714.00	18,714.00
8	1	Diode Bridge	N/A	6,948.00	6,948.00
9	1	Subpanel	N/A	2,878.40	2,878.40
10	1	Control Board	Y	1,350.00	1,350.00
11	1	Enclosure	Y	2,000.00	2,000.00
		TOTAL:			**102,611.40**

4.3.4 Line Matrix for 5.0-MW MV Turbine

The 5.0-MW line side inverter uses a multi-level (three-level), neutral point clamped inverter system to supply current to the 4160 V padmount transformer. This inverter structure has the advantage that the semiconductor only needs to block half of the total DC bus voltage. Also the multi-level voltage output has a smaller harmonic content than the two-level inverter and as such, the output filter requirements are reduced.

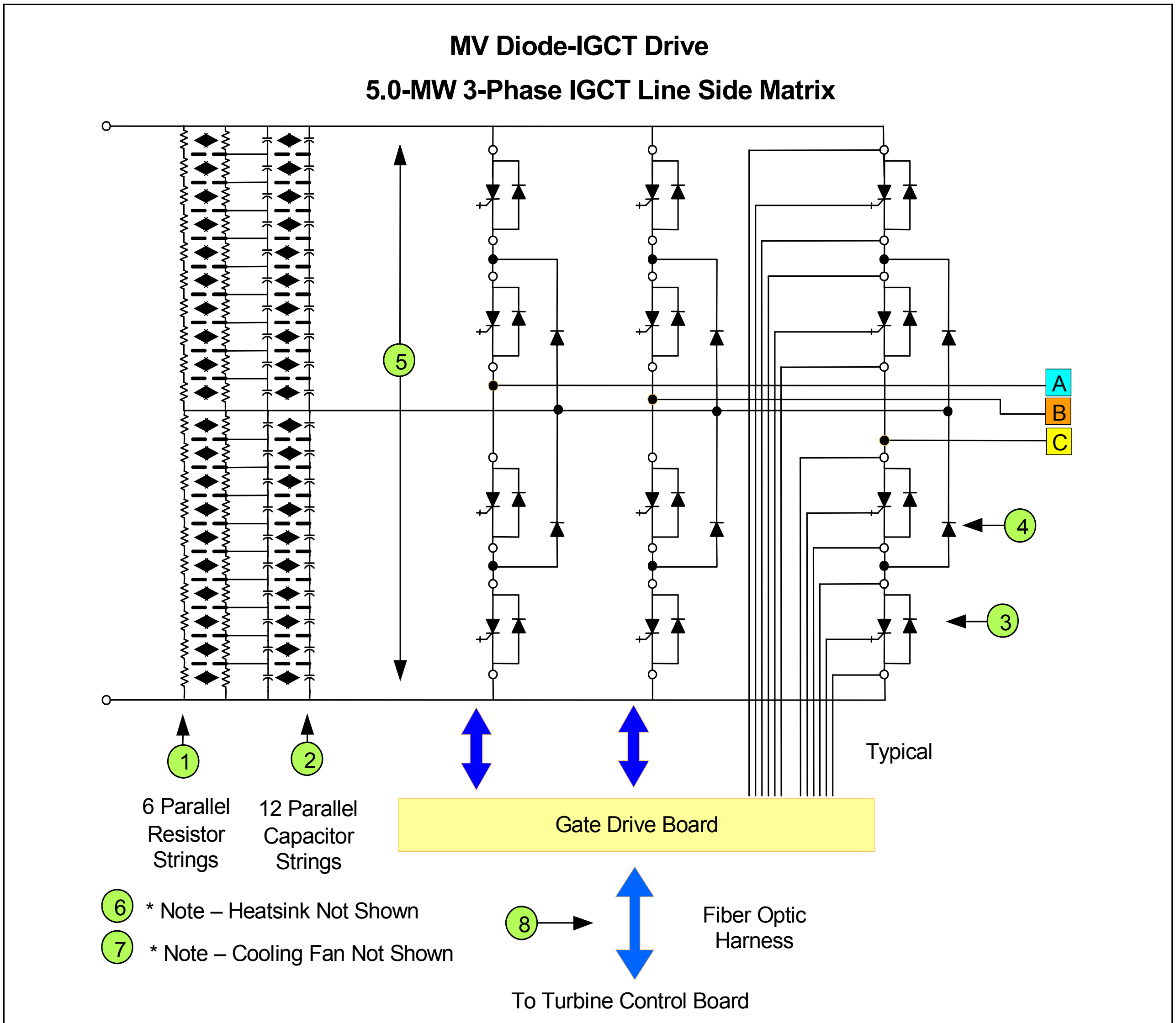


Figure 4-7 Line matrix schematic, 5.0-MW MV turbine

Table 4-12 Line matrix costing, 5.0-MW MV turbine

5.0-MW MV Diode-IGCT Matrix BOM

Item #	Qty	Description	Quoted	Unit Cost	Ext Cost
1	120	Resistor, Balance, 10k, 25W	Y	3.00	360.00
2	240	Capacitor, 8200uF, 450Vdc	Y	47.00	11,280.00
3	12	IGCT, 1200A, 6.6kV	Y	962.00	11,544.00
4	6	Diode, Freewheel, 1200A, 10kV	Y	850.00	5,100.00
5	1	Assy, Laminated Bus	Y	1,200.00	1,200.00
6	1	Heatsink	Y	2,500.00	2,500.00
7	1	Cooling Fan	Y	500.00	500.00
8	1	Fiber Optic Harness	Y	118.00	118.00
		TOTAL:			**32,602.00**

4.3.5 Chopper for 5.0-MW MV Turbine

A chopper is used in the 5.0-MW converter for the same reasons that were discussed in the 3.0-MW section. Please note, however, that because of the higher DC voltage here, semiconductors are applied in a series configuration in the chopper.

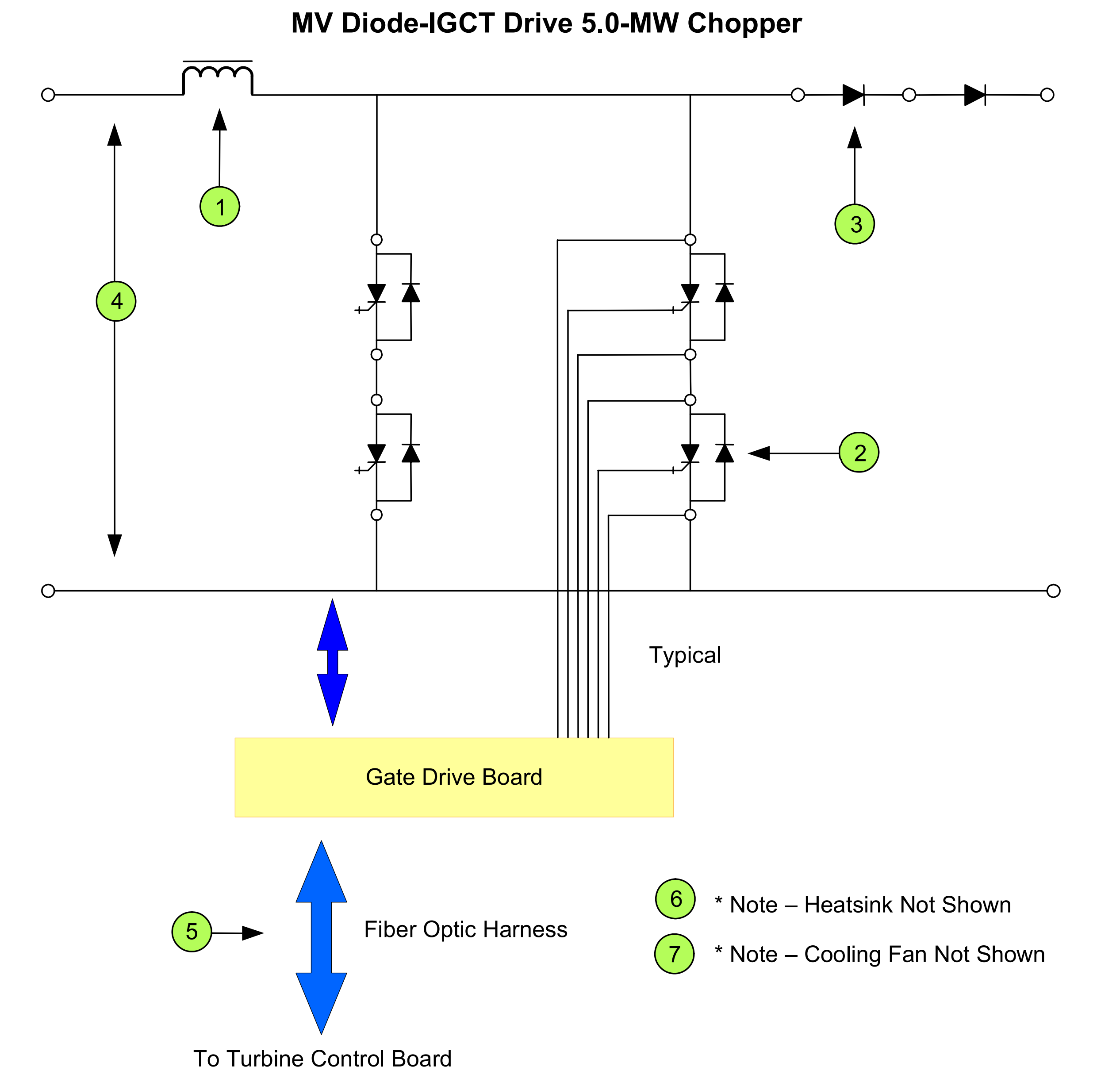


Figure 4-8 5.0-MW MV chopper diagram

Table 4-13 5.0-MW MV chopper BOM

5.0-MW MV Diode-IGCT Chopper BOM

Item #	Qty	Description	Quoted	Unit Cost	Ext Cost
1	1	Inductor, Chopper, 1mH 900Adc	Y	7,800.00	7,800.00
2	6	IGCT, 1200A, 6.6kV	Y	962.00	5,772.00
3	2	Diode, Chopper, 1200A, 6.6kV	Y	412.00	824.00
4	1	Assy, Laminated Bus	Y	1,200.00	1,200.00
6	1	Fiber-Optic Harness	Y	118.00	118.00
7	1	Heatsink	Y	2,500.00	2,500.00
8	1	Cooling Fan	Y	500.00	500.00
		TOTAL:			**18,714.00**

4.3.6 Line Filter for 5.0-MW MV Turbine

The line filter for the 5.0-MW, multi-level inverter is shown and costed below.

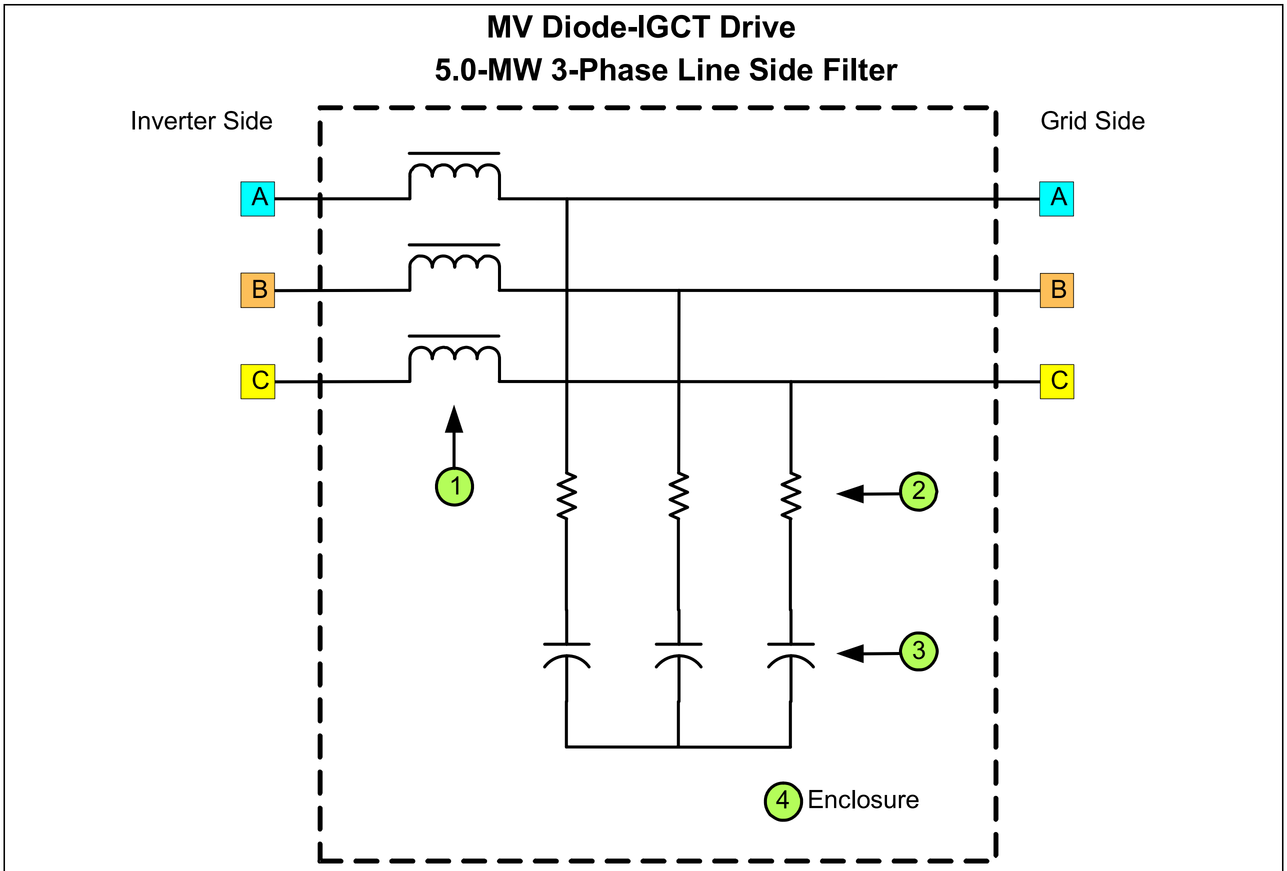


Figure 4-9 Line filter schematic, 5.0-MW MV turbine

Table 4-14 Line filter costing, 5.0-MW MV turbine

5.0-MW MV Diode-IGCT Filter BOM

Item #	Qty	Description	Quoted	Unit Cost	Ext Cost
1	1	Reactor, PWM, 6mH, 700A, 3 Phase, 4160V	Y	24,000.00	24,000.00
2	3	Resistor, Stainless, 3 phase, 0.1 Ω/Phase	Y	500.00	1,500.00
3	1	Capacitor, 100 kVAR, 3 Phase, 4160V	Y	1,850.00	1,850.00
4	1	Enclosure	Y	800.00	800.00
		TOTAL:			**28,150.00**

4.3.7 Converter Subpanel 5.0-MW MV Turbine

The subpanel components and costing for the 5.0-MW turbine are as shown below.

Table 4-15 Converter subpanel costing, 5.0-MW MV turbine

5.0- MW MV Diode-IGCT Sub-Panel BOM

Item #	Qty	Description	Quoted	Unit Cost	Ext Cost
1	1	Xfmr, 3 phase Isolation, 4160:240, 5kVA	Y	500.00	500.00
2	1	Fab, Panel, Power Distribution	Y	50.00	50.00
3	1	Switch, Disconnect, 80A, 600V, 2p	Y	180.00	180.00
4	2	Circuit Breaker, 30A, 600V, 3-P	Y	120.80	241.60
5	3	Fuse, 30A, 600V	Y	5.00	15.00
6	3	Fuseblock, 100A, 600V	Y	5.00	15.00
7	2	Capacitor, Electrolytic, 300uF, 250V	Y	15.00	30.00
8	1	Assy, Harness, Main	Y	300.00	300.00
9	1	Circuit Breaker, 20A, 600V	Y	93.80	93.80
10	1	Circuit Breaker, 2A, 600V	Y	70.00	70.00
11	4	SSR, 12A, 200Vdc, MOSFET OUT	Y	17.00	68.00
12	250	350 MCM 2000V Cable	Y	3.86	965.00
13	1	Transformer, Control, 4kVA 1ph	Y	350.00	350.00
		TOTAL:			**2,878.40**

4.3.8 Passive Rectifier for 5.0-MW MV Turbine

The passive rectifier for the 5.0-MW, MV converter system is shown below. Note the series-connected diode rectifiers. Losses are managed by a heatsink and fan similar to the LV case. Losses are minimal in the rectifier circuit.

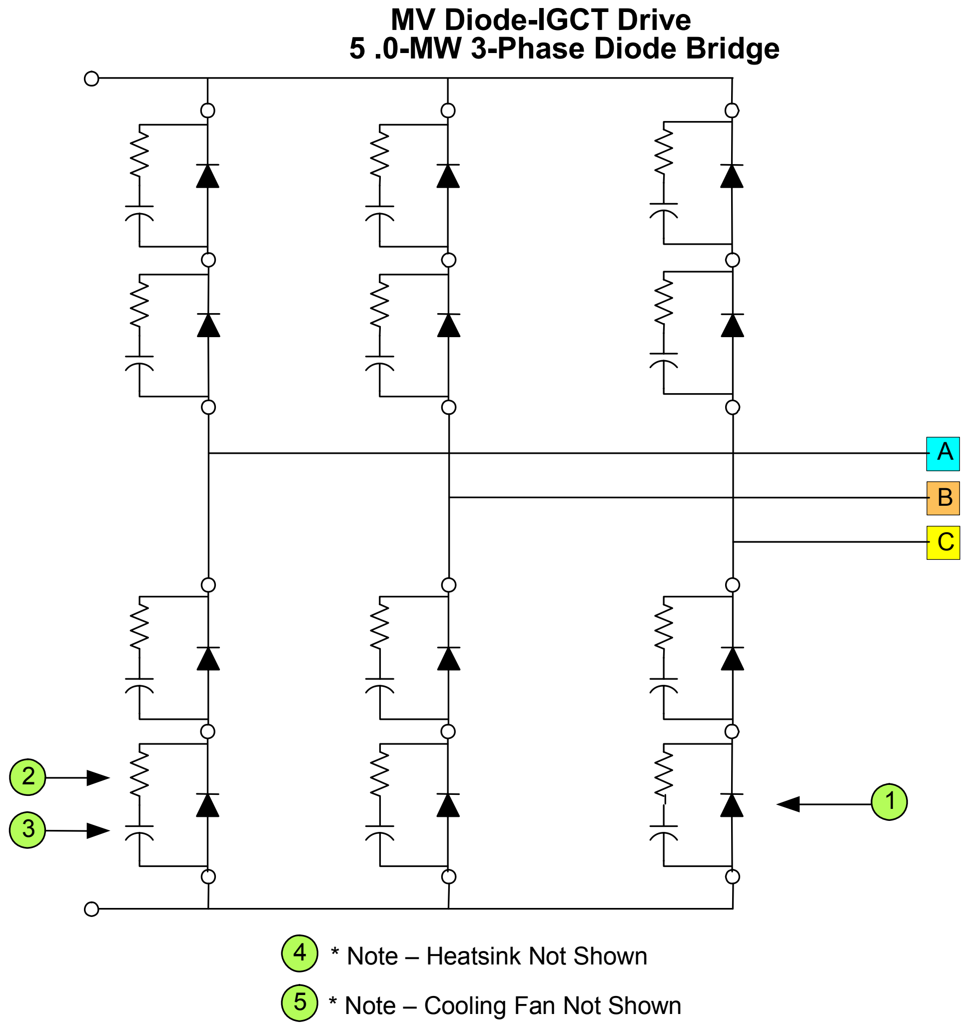


Figure 4-10 Passive rectifier diagram, 5.0-MW MV turbine

Table 4-16 Passive rectifier costing, 5.0-MW MV turbine

5.0-MW MV Diode-IGCT Diode Bridge Rectifier BOM

Item #	Qty	Description	Quoted	Unit Cost	Ext Cost
1	12	Diode, 1200A, 6.6kV, Fast Recovery	Y	418.00	5,016.00
2	12	Resistor	Y	12.00	144.00
3	12	Capacitor	Y	5.00	60.00
4	1	Heatsink, Clamps, Terminations	Y	1,372.00	1,372.00
5	1	Cooling Fan and Switchgear	Y	356.00	356.00
		TOTAL:			**6,948.00**

4.4 Electrical System BOM for 7.5-MW MV Turbine

The 7.5-MW MV converter system consists of a passive rectifier, chopper, and IGCT inverter system. Table 4-17 lists the electrical system BOM for the 7.5-MW MV voltage-source inverter turbine. The material cost totalized at the bottom of the table will be compared with the LV design in the COE models of Section 5.

Table 4-17 7.5-MW MV Electrical System BOM

#	Item	Description	Cost
1	Generator	7.5 MW, 105 Deg. C rise, 6 pole, open drip-proof, flange mounted, 33% reactance, wye connected, form wound, 97% F.L. efficiency	$ 248,312
2	Tower Pendant Cables	1285 ft. of 5/8kV shielded, 90 deg C., 500 MCM, normal stranding	$ 9,589
3	Tower Pendant Cables (festooning)	227 ft., 5/8 kV, high stranded, 500 MCM DLO	$ 1,862
4	LV Inverter	Voltage source inverter per attached included BOM's	$ 191,218
5	Transformer and Switchgear	7.5MVA, Oil filled padmount, outdoor rated, 34.5 kV primary, 6900 V wye secondary	$ 51,050
		Total Cost	$ 502,031

4.4.1 Converter System for 7.5-MW MV Turbine

Material costing for this converter is detailed below. Note that the schematics and figure are not included in this section as these are identical to the corresponding subassemblies in the 5.0-MW converter section; the architecture of the rectifier, chopper, and inverter is identical to the 5.0-MW case. One important point regarding the 7.5-MW system is that it operates at 6,900 V. Systems operating at this voltage level typically use three 6.6-kV power semiconductors in series to achieve the necessary blocking voltage margin. In this costing exercise, the use of two 10-kV IGCTs is assumed. These devices are much more in a development stage than those discussed to this point in the report. As such, the costing of this converter and the commercial availability of such parts remains a risk. Development IGCT devices have been built at these voltage levels, and their operation in multi-level inverters at 6900V are discussed in [3], [4]. Further, the wide band-gap materials, such as silicon carbide, are ideal candidates for the higher voltage devices.

4.4.2 Converter System Pricing for 7.5-MW MV Turbine

Table 4-18 Pricing spreadsheet for 7.5-MW MV Converter System

7.5-MW Permanent Magnet Drive			
Direct Variable Materials (1)	$ 139,025.69	$ 139,025.69	$ 139,025.69
Direct Variable Labor (2)	$ 2,497.86	$ 2,497.86	$ 2,497.86
Direct Fixed Costs (3)	$ 1,890.00	$ 1,890.00	$ 1,890.00
Total Direct Costs	$ 143,413.55	$ 143,413.55	$ 143,413.55
Gross Margin (4)	20%	25%	30%
Sales Price	$ 179,266.94	$ 191,218.07	$ 204,876.50

(1) Annual production = 250 Turbines
(2) Includes 3% freight in
(3) Assumes 70% utilization and 30% fringe benefits
(4) Includes $120k rent, $200k capital equip, $68k utility and $85k supervision (annual costs)
(5) Gross Margin = (Sales Price - Direct Cost)/Sales Price

4.4.3 Converter Material Breakdown and BOM for 7.5-MW MV Turbine

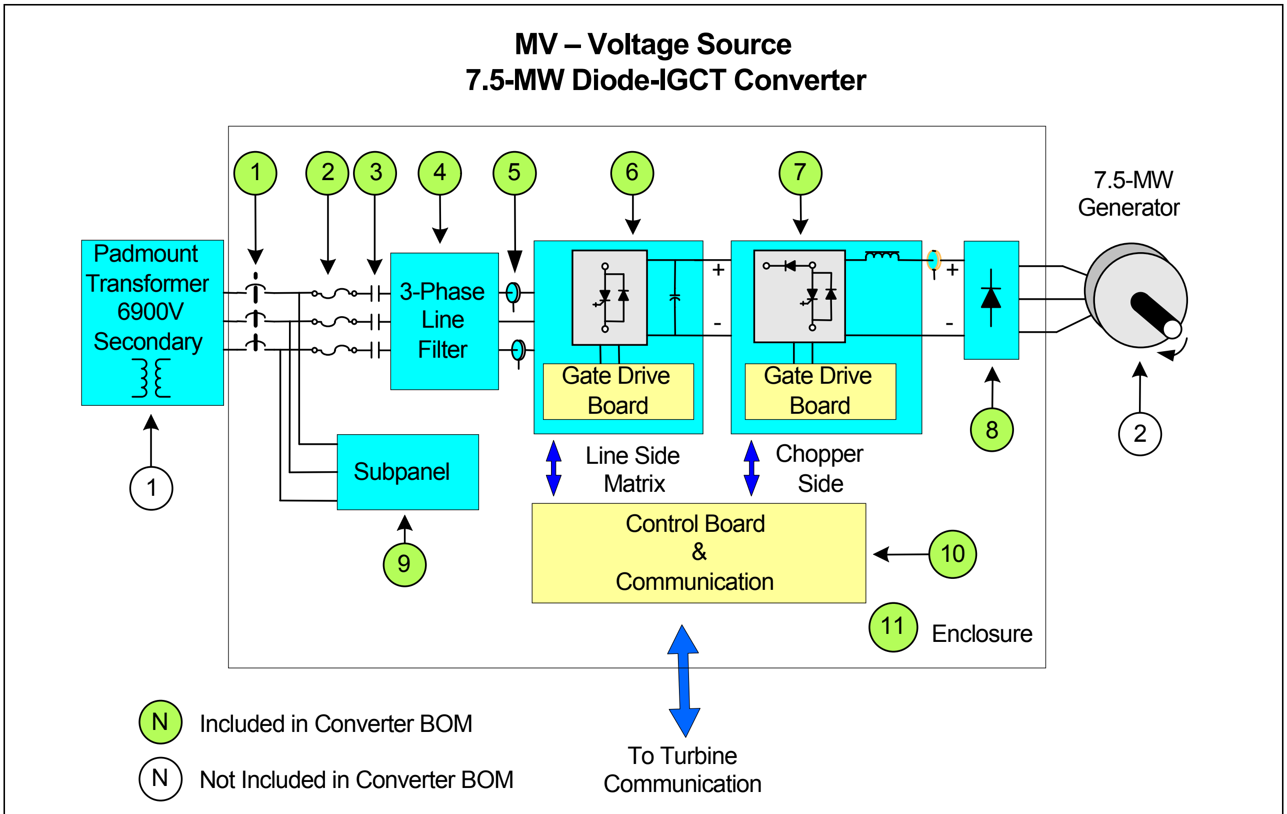


Figure 4-11 7.5-MW MV turbine converter diagram

Table 4-19 7.5-MW MV turbine converter BOM

7.5-MW MV Diode-IGCT Converter BOM

Item #	Qty	Description	Quoted	Unit Cost	Ext Cost
1	1	Circuit Breaker, 800A, 10kVAC, 3-Pole, Line	Y	4,327.00	4,327.00
2	1	Fuse, 800A, 10kVAC, 3-Pole	Y	3,964.00	3,964.00
3	1	Contactor, 800A, 10kVAC, 3-Pole, Line	Y	4,168.00	4,168.00
4	1	Line Filter, 3 Phase	N/A	29,150.00	29,150.00
5	3	Current Transducers 900A	Y	450.00	1,350.00
6	1	Assy, IGCT Matrix, 3-Phase, Line	N/A	49,986.00	49,986.00
7	1	Assy, Diode-IGCT Chopper	N/A	24,010.00	24,010.00
8	1	Diode Bridge	N/A	10,228.00	10,228.00
9	1	Subpanel	N/A	4,443.40	4,443.40
10	1	Control Board	Y	1,350.00	1,350.00
11	1	Enclosure	Y	2,000.00	2,000.00
		TOTAL:			**134,976.40**

4.4.4 Line Matrix for 7.5-MW MV Turbine

A schematic for the Line matrix can be seen under the 5.0-MW discussion.

Table 4-20 Line matrix costing, 7.5-MW MV turbine

7.5-MW MV Diode-IGCT Matrix BOM

Item #	Qty	Description	Quoted	Unit Cost	Ext Cost
1	192	Resistor, Balance, 10k, 25W	Y	3.00	576.00
2	384	Capacitor, 8200uF, 450Vdc	Y	47.00	18,048.00
3	12	IGCT, 1200A, 10kV	Y	1,312.00	15,744.00
4	12	Diode, Freewheel, 1200A, 10kV	Y	850.00	10,200.00
5	1	Assy, Laminated Bus	Y	1,800.00	1,800.00
6	1	Heatsink	Y	3,000.00	3,000.00
7	1	Cooling Fan	Y	500.00	500.00
8	1	Fiber-Optic Harness	Y	118.00	118.00
		TOTAL:			**49,986.00**

4.4.5 Chopper for 7.5-MW MV Turbine

The schematic for the chopper is the same as in the 5.0-MW costing section. Cost differences reflect the different values required for 7.5-MW operation.

Table 4-21 7.5-MW MV chopper BOM

7.5-MW MV Diode-IGCT Chopper BOM

Item #	Qty	Description	Quoted	Unit Cost	Ext Cost
1	1	Inductor, Chopper, 1mH 900Adc	Y	12,000.00	12,000.00
2	4	IGCT, 1200A, 10kV	Y	1,312.00	5,248.00
3	2	Diode, Chopper, 1200A, 10kV	Y	672.00	1,344.00
4	1	Assy, Laminated Bus	Y	1,800.00	1,800.00
5	1	Fiber-Optic Harness	Y	118.00	118.00
6	1	Heatsink	Y	3,000.00	3,000.00
7	1	Cooling Fan	Y	500.00	500.00
		TOTAL:			**24,010.00**

4.4.6 Line Filter for 7.5-MW MV Turbine

Costing for the 7.5-MW line filter is given below.

Table 4-22 Line filter costing, 7.5-MW MV turbine

7.5-MW MV Diode-IGCT Filter BOM

Item #	Qty	Description	Quoted	Unit Cost	Ext Cost
1	1	Reactor, PWM, 6mH, 700A, 3 Phase, 6900V	Y	24,000.00	24,000.00
2	3	Resistor, Stainless, 3 phase, 0.1Ω/Phase	Y	500.00	1,500.00
3	1	Capacitor, 100 kVAR, 3 Phase, 6900V	Y	2,850.00	2,850.00
4	1	Enclosure	Y	800.00	800.00
		TOTAL:			**29,150.00**

4.4.7 Converter Subpanel for 7.5-MW MV Turbine

The components mounted and wired on the 7.5-MW converter are the same as in the 5.0-MW case.

Table 4-23 Converter subpanel costing, 7.5-MW MV turbine

7.5-MW MV Diode-IGCT Subpanel BOM

Item #	Qty	Description	Quoted	Unit Cost	Ext Cost
1	1	Xfmr, 3 phase Isolation, 6900:240, 5kVA	Y	1,500.00	1,500.00
2	1	Fab, Panel, Power Distribution	Y	50.00	50.00
3	1	Switch, Disconnect, 80A, 600V, 2p	Y	180.00	180.00
4	2	Circuit Breaker, 30A, 600V, 3-P	Y	120.80	241.60
5	3	Fuse, 30A, 600V	Y	5.00	15.00
6	3	Fuseblock, 100A, 600V	Y	5.00	15.00
7	2	Capacitor, Electrolytic, 300uF, 250V	Y	15.00	30.00
8	1	Assy, Harness, Main	Y	300.00	300.00
9	1	Circuit Breaker, 20A, 600V	Y	93.80	93.80
10	1	Circuit Breaker, 2A, 600V	Y	70.00	70.00
11	4	SSR, 12A, 200Vdc, MOSFET OUT	Y	17.00	68.00
12	250	350 MCM 15kV Cable	Y	6.12	1,530.00
13	1	Transformer, Control, 4kVA 1ph	Y	350.00	350.00
		TOTAL:			**4,443.40**

4.4.8 Passive Rectifier for 7.5-MW MV Turbine

The passive rectifier uses two 10-kV diode rectifiers in series for each element.

Table 4-24 Passive rectifier costing, 7.5-MW MV turbine

7.5-MW MV Diode-IGCT Diode Bridge Rectifier BOM

Item #	Qty	Description	Quoted	Unit Cost	Ext Cost
1	12	Diode, 1200A, 10kV	Y	672.00	8,064.00
2	12	Resistor	Y	12.00	144.00
3	12	Capacitor	Y	5.00	60.00
4	1	Heatsink	Y	1,604.00	1,604.00
5	1	Cooling Fan	Y	356.00	356.00
		TOTAL:			**10,228.00**

4.5 References

1 Yuan, X., et al. "Fundamentals of a New Diode-Clamping Multi-Level Indicator." IEEE Transaction on Power Electronics, July 2000.

2 Integrated Gate Commutated Thyristors Application Notes. "Applying IGCT Gate Units." ABB, December 2002..

3 Eicher, S., et al. "The 10-kV IGCT – A New Device for Medium Voltage Drives." Proceedings of IEEE Industry Applications Society, Rome, 2000.

4 Lyons, J., et al. "Innovation IGCT Main Drives." Proceedings of IEEE Industry Applications Society, Rome, 2000.

5 Electrical System Bill of Materials – MV, Current-Source Inverter Topology

In this section, all turbines use an MV, current-source inverter to supply power back to the low-side MV connection on the padmount transformer. Unlike voltage-source inverters, the current-source inverter requires the DC bus voltage to remain below the peak of the AC line. During ride-through events, the rectified generator voltage, which sets the DC bus voltage, is well above the faulted AC line voltage and can lead to uncontrolled currents and a fault condition. To prevent this situation, a controlled rectifier is placed on the generator. The controlled rectifier keeps the DC bus voltage below the peak of the AC line for all line conditions. A current-source inverter with a controlled rectifier allows for maintained unit operation during utility fault ride-through conditions. Another beneficial effect of the requirement that the DC bus voltage be less than the peak of the AC line is that the generator can operate down to near-zero speed. A current-source inverter design thus extends the speed range of the turbine drive train and slightly increases the energy capture over the restricted speed range case.

As in Section 4, North American MV electrical systems are assumed. The specific voltages used are 2,400 V at 3.0 MW; 4,160 V at 5.0 MW; and 6,900 V at 7.5 MW. These voltages were selected to keep the AC line currents at about 700 amps for all three turbines; this is the most cost-effective MV sizing.

5.1 Section Organization

This section is organized in the same way as Sections 2.0 and 3.0. Deviations from these two sections are pointed out.

5.2 Electrical System BOM for 3.0-MW MV Turbine

Table 5-1 lists the electrical system BOM for the 3.0-MW, MV turbine. The material cost totalized at the bottom of the table will be compared with the LV design in the COE models of Section 5.

Table 5-1 3.0-MW MV electrical system BOM

#	Item	Description	Cost
1	Generator	3.0 MW, 105 Deg. C rise, 6 pole, open drip-proof, flange mounted, 33% reactance, wye connected, form wound, 97% F.L. efficiency	$ 114,000
2	Tower Pendant Cables	812 ft. of 5kV shielded, 90 deg C., 600 MCM,normal stranding	$ 7,578
3	Tower Pendant Cables (festooning)	143 ft., 5 kV, high stranded, 600 MCM DLO	$ 1,471
4	LV Inverter	Voltage source inverter per attached included BOM's	$ 83,660
5	Transformer and Switchgear	3MVA, Oil filled padmount, outdoor rated, 34.5 kV primary, 2400 V wye secondary	$ 34,212
		Total Cost	$ 240,921

5.2.1 Converter System for 3.0-MW MV Turbine

The 3.0-MW MV variable-speed converter system consists of a generator-controlled rectifier and current-source IGCT inverter system. The electrical system consists of a single generator output and single converter system. This is in contrast to the highly paralleled architecture of the LV system, which uses 625-kW or 750-kW converter modules.

Table 5-2 Pricing spreadsheet for 3.0-MW MV turbine

3.0-MW Synchronous Machine Drive			
Direct Variable Materials (1)	$ 58,881.39	$ 58,881.39	$ 58,881.39
Direct Variable Labor (2)	$ 2,135.71	$ 2,135.71	$ 2,135.71
Direct Fixed Costs (3)	$ 1,728.00	$ 1,728.00	$ 1,728.00
Total Direct Costs	$ 62,745.11	$ 62,745.11	$ 62,745.11
Gross Margin (4)	20%	25%	30%
Sales Price	$ 78,431.38	$ 83,660.14	$ 89,635.87

(1) Annual production = 250 Turbines
(2) Includes 3% freight in
(3) Assumes 70% utilization and 30% fringe benefits
(4) Includes $120k rent, $200k capital equip, $27k utility and $85k supervision (annual costs)
(5) Gross Margin = (Sales Price - Direct Cost)/Sales Price

5.2.2 Converter Material Breakdown and BOM for 3.0-MW MV Turbine

A basic diagram and material costs of the converter main assembly are shown below, with subassembly detail shown in the subsequent four sections. Firm quotations for identified components are identified in the Quoted column, with the balance of subassemblies estimated by the project team and detailed separately.

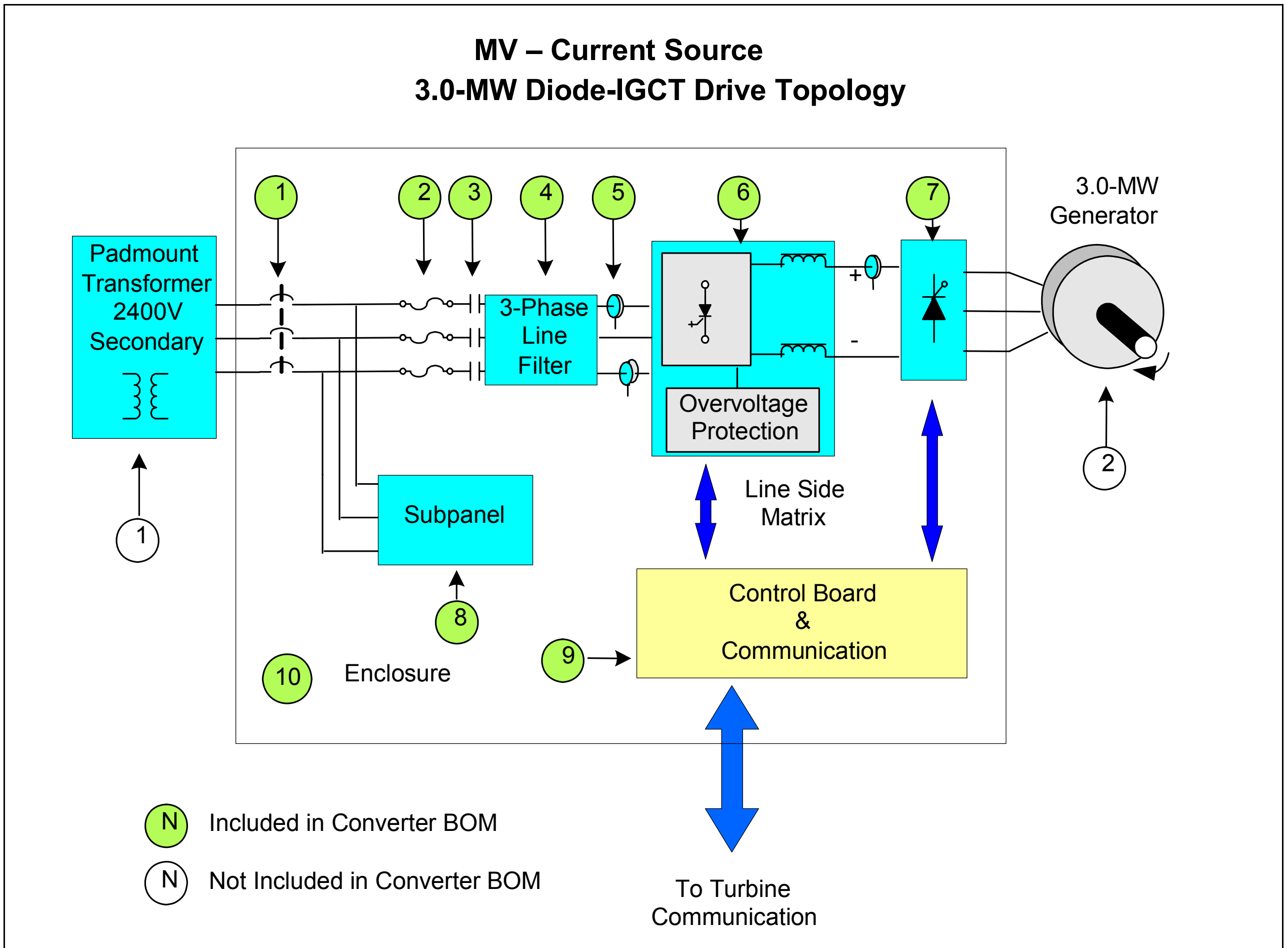


Figure 5-1 3.0-MW MV converter diagram

Table 5-3 3.0-MW MV converter BOM

3.0-MW MV Diode-IGCT Converter BOM

Item #	Qty	Description	Quoted	Unit Cost	Ext Cost
1	1	Circuit Breaker, 800A, 2400VAC, 3-P, Line	Y	3,106.00	3,106.00
2	1	Fuse, 800A, 2400VAC, 3-Pole	Y	2,798.00	2,798.00
3	1	Contactor, 800A, 2400VAC, 3-Pole, Line	Y	2,715.00	2,715.00
4	1	Line Filter, 3 Phase	N/A	8,150.00	8,150.00
5	3	Current Transducers 900A	Y	100.00	300.00
6	1	Assy, IGCT Matrix, 3-Phase, Line	N/A	24,538.00	24,538.00
7	1	Assy, Active Rectifier	N/A	8,046.00	8,046.00
8	1	Subpanel	N/A	4,163.40	4,163.40
9	1	Control Board	Y	1,350.00	1,350.00
10	1	Enclosure	Y	2,000.00	2,000.00
		TOTAL:			**57,166.40**

5.2.3 Line Matrix for 3.0-MW MV Turbine

The line side inverter matrix is shown below and consists of six symmetrical, 6.6-kV IGCT devices. The existence of the large DC link reactor presents potential over-voltage conditions. To protect against this over-voltage condition, the protection circuit consisting of passive diodes, capacitor, and transient suppressor is added. This is shown in the schematic below. The diodes are rated well below the main converter device ratings.

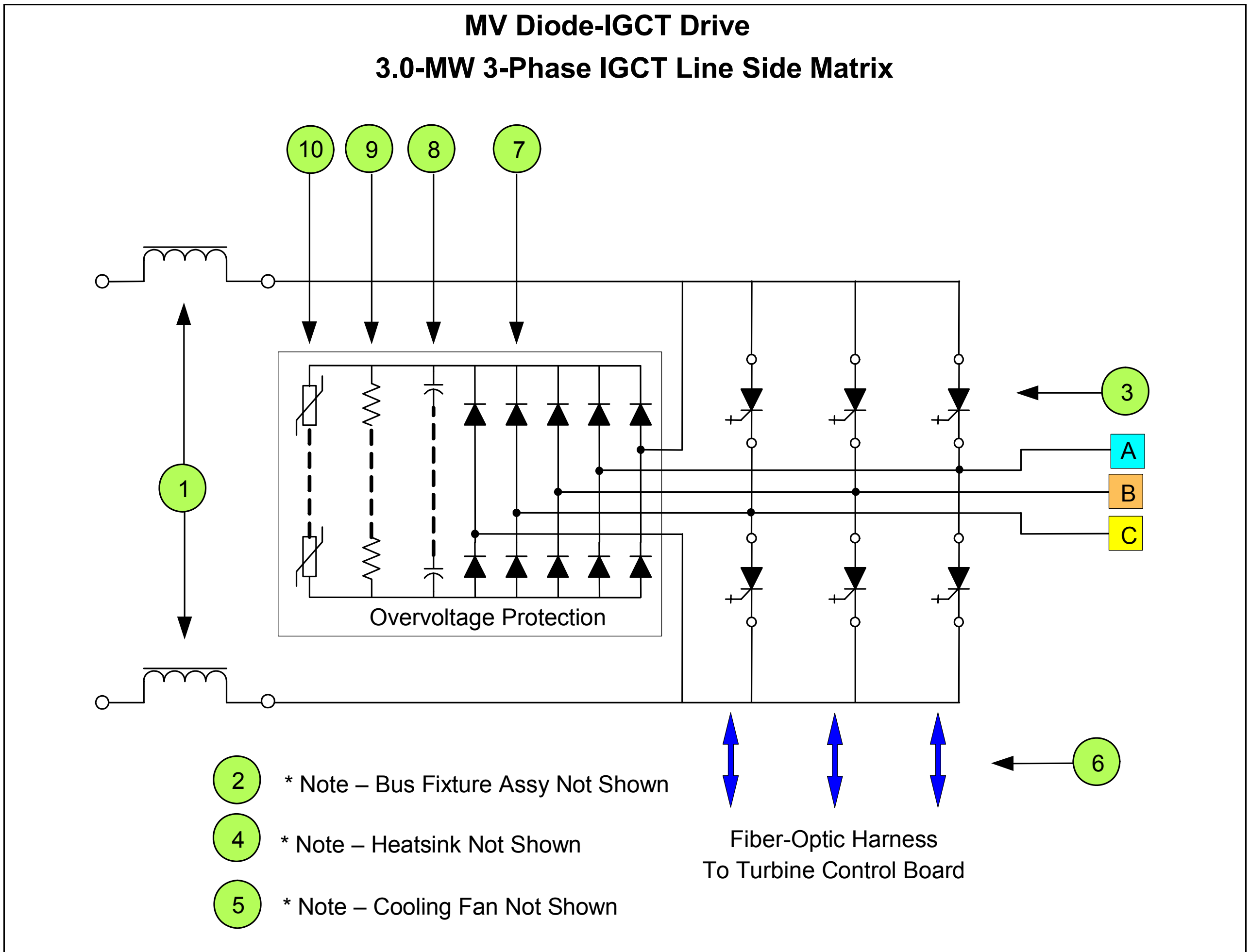


Figure 5-2 Line matrix schematic, 3.0-MW MV turbine

Table 5-4 Line matrix costing, 3.0-MW MV turbine

3.0-MW MV Diode-IGCT Matrix BOM

Item #	Qty	Description	Quoted	Unit Cost	Ext Cost
1	1	Inductor, Link, 2mH, 800A	Y	6,000.00	6,000.00
2	1	Assy, Bus Fixture	Y	500.00	500.00
3	6	IGCT, 1200A, 6600V	Y	1,800.00	10,800.00
4	1	Heatsink	Y	2,500.00	2,500.00
5	1	Cooling Fan	Y	500.00	500.00
6	1	Fiber-Optic Harness	Y	118.00	118.00
7	10	Diode, Overvoltage Protection, 6600V, 200A	Y	332.00	3,320.00
8	10	Capacitor, 8200uF, 450Vdc	Y	47.00	470.00
9	10	Resistor, Balance, 10k, 25W	Y	3.00	30.00
10	4	MOV, 1000V	Y	75.00	300.00
		TOTAL:			**24,538.00**

5.2.4 Line Filter for 3.0-MW MV Turbine

The line filter for the current-source inverter is shown in Figure 4-3. Note that the components are arranged in a "duality" arrangement when compared to the voltage-source inverter; i.e., parallel capacitors are connected to the output of the inverter and then a series inductor to the transformer.

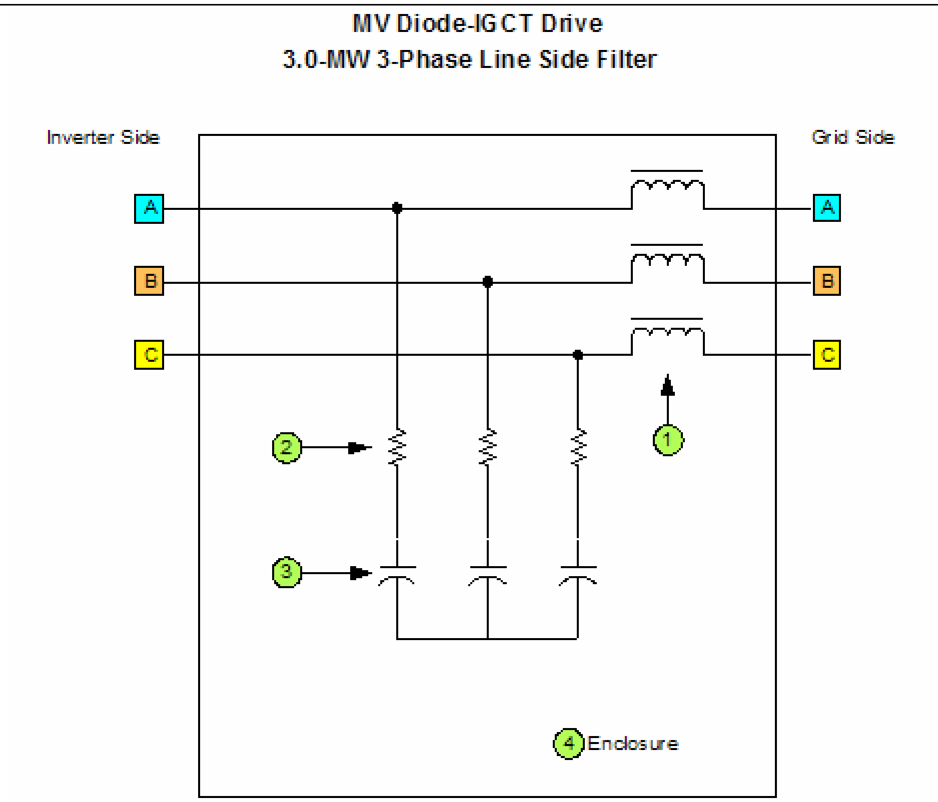


Figure 5-3 Line filter schematic, 3.0-MW MV turbine

Table 5-5 Line filter costing, 3.0-MW MV turbine

3.0-MW MV Diode-IGCT Filter BOM

Item #	Qty	Description	Quoted	Unit Cost	Ext Cost
1	1	Reactor, Line, 200uH, 750A, 3 Phase, 2400V	Y	4,000.00	4,000.00
2	3	Resistor, Stainless, 3 phase, 0.1 Ω/Phase	Y	500.00	1,500.00
3	1	Capacitor, 100 kVAR, 3 Phase, 4160V	Y	1,850.00	1,850.00
4	1	Enclosure	Y	800.00	800.00
		TOTAL:			**8,150.00**

5.2.5 Converter Subpanel for 3.0-MW MV Turbine

The current-source inverter subpanel contains the same components and elements as the voltage-source inverter. Costing for the subpanel is provided below.

Table 5-6 Converter subpanel costing, 3.0-MW MV turbine

3.0-MW MV Diode-IGCT Sub-Panel BOM

Item #	Qty	Description	Quoted	Unit Cost	Ext Cost
1	1	Xfmr, 3 phase Isolation, 2400:240, 5kVA	Y	1,500.00	1,500.00
2	1	Fab, Panel, Power Distribution	Y	50.00	50.00
3	1	Switch, Disconnect, 80A, 600V, 2p	Y	180.00	180.00
4	2	Circuit Breaker, 30A, 600V, 3-P	Y	120.80	241.60
5	3	Fuse, 30A, 600V	Y	5.00	15.00
6	3	Fuseblock, 100A, 600V	Y	5.00	15.00
7	2	Capacitor, Electrolytic, 300uF, 250V	Y	15.00	30.00
8	1	Assy, Harness, Main	Y	300.00	300.00
9	1	Circuit Breaker, 20A, 600V	Y	93.80	93.80
10	1	Circuit Breaker, 2A, 600V	Y	70.00	70.00
11	4	SSR, 12A, 200Vdc, MOSFET OUT	Y	17.00	68.00
12	250	350 MCM 15kV Cable	Y	5.00	1,250.00
13	1	Transformer, Control, 4kVA 1ph	Y	350.00	350.00
		TOTAL:			**4,163.40**

5.2.6 Controlled Rectifier for 3.0-MW MV Turbine

The controlled rectifier is unique to the current-source inverter. The operation is quite simple. During normal running conditions, the controlled rectifier is fired at a zero-degree delay angle; this is equivalent to passive rectifier operation. Under a transmission ride-through event, however, the rectifier is phased back to reduce the DC bus voltage to prevent uncontrolled current flow. The controlled rectifier uses 6.6-kV SCR devices and appropriate triggering and control board subassemblies.

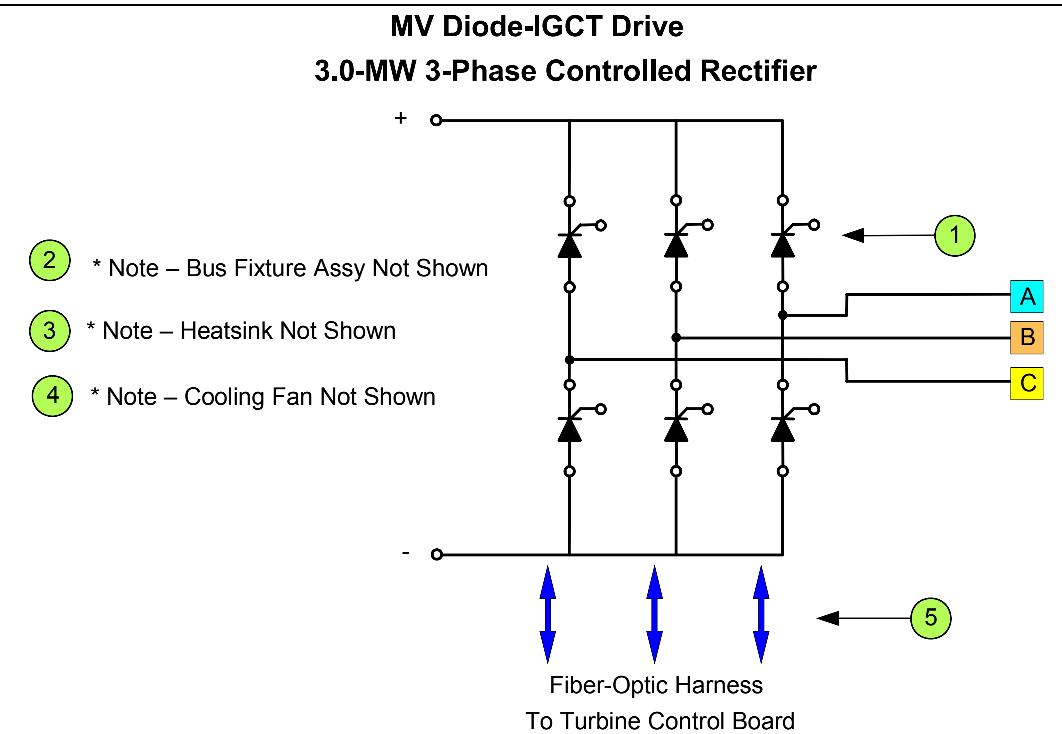


Figure 5-4 Controlled rectifier, 3.0-MW MV turbine

Table 5-7 Controlled rectifier costing, 3.0-MW MV turbine

3.0-MW MV Diode-IGCT Controlled Rectifier BOM

Item #	Qty	Description	Quoted	Unit Cost	Ext Cost
1	6	SCR, 800A, 6600V	Y	832.00	4,992.00
2	1	Bus Fixture Assy	Y	1,208.00	1,208.00
3	1	Heatsink, Clamps, Terminations	Y	1,372.00	1,372.00
4	1	Cooling Fan and Switchgear	Y	356.00	356.00
5	1	Fiber-Optic Harness	Y	118.00	118.00
		TOTAL:			**8,046.00**

5.3 Electrical System BOM for 5.0-MW MV Turbine

Table 5-8 lists the electrical system BOM for the 5.0-MW, MV turbine. The material cost totalized at the bottom of the table will be compared with the LV and MV designs in the COE models of Section 5.

Table 5-8 5.0-MW MV electrical system BOM

#	Item	Description	Cost
1	Generator	5.0 MW, 105 Deg. C rise, 6 pole, open drip-proof, flange mounted, 33% reactance, wye connected, form wound, 97% F.L. efficiency	$ 164,000
2	Tower Pendant Cables	8354 ft. of 5kV shielded, 90 deg C., 500 MCM, normal stranding	$ 7,795
3	Tower Pendant Cables (festooning)	184 ft., 5 kV, high stranded, 500 MCM DLO	$ 1,513
4	LV Inverter	Voltage source inverter per attached included BOM's	$ 115,240
5	Transformer and Switchgear	5MVA, Oil filled padmount, outdoor rated, 34.5 kV primary, 4160 V wye secondary	$ 41,354
		Total Cost	$ 329,902

5.3.1 Converter System for 5.0-MW MV Turbine

The 5.0-MW MV variable-speed converter system consists of a generator-controlled rectifier and current-source IGCT-based inverter system. The electrical system consists of a single generator output and single converter system. The higher voltage (i.e., 4160 V) system requires series connection of power semiconductors. Pricing for the 5.0-MW converter system is provided in this section.

Table 5-9 Converter system pricing spreadsheet, 5.0-MW MV turbine

5.0-MW Synchronous Machine Drive			
Direct Variable Materials (1)	$ 82,466.33	$ 82,466.33	$ 82,466.33
Direct Variable Labor (2)	$ 2,163.57	$ 2,163.57	$ 2,163.57
Direct Fixed Costs (3)	$ 1,800.00	$ 1,800.00	$ 1,800.00
Total Direct Costs	$ 86,429.90	$ 86,429.90	$ 86,429.90
Gross Margin (4)	20%	25%	30%
Sales Price	$ 108,037.38	$ 115,239.87	$ 123,471.29

(1) Annual production = 250 Turbines
(2) Includes 3% freight in
(3) Assumes 70% utilization and 30% fringe benefits
(4) Includes $120k rent, $200k capital equip, $45k utility and $85k supervision (annual costs)
(5) Gross Margin = (Sales Price - Direct Cost)/Sales Price

5.3.2 Converter Material Breakdown and BOM for 5.0-MW MV Turbine

A basic diagram and material costs of the 5.0-MW converter main assembly are shown in Figure 4-5.

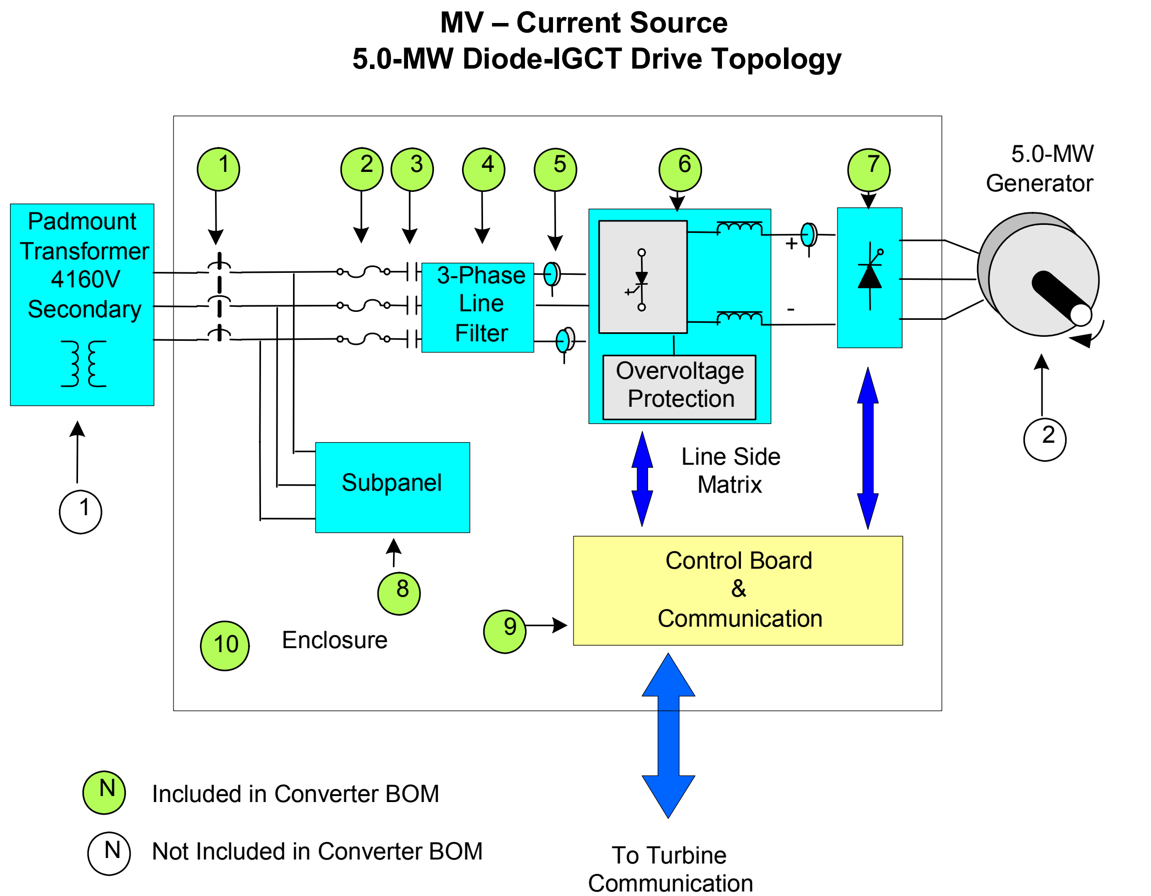


Figure 5-5 5.0-MW MV converter diagram

Table 5-10 5.0-MW MV converter BOM

5.0-MW MV Diode-IGCT Converter BOM

Item #	Qty	Description	Quoted	Unit Cost	Ext Cost
1	1	Circuit Breaker, 800A, 5kVAC, 3-Pole, Line	Y	3,106.00	3,106.00
2	1	Fuse, 800A, 5kVAC, 3-Pole	Y	2,798.00	2,798.00
3	1	Contactor, 800A, 5kVAC, 3-Pole, Line	Y	2,715.00	2,715.00
4	1	Line Filter, 3 Phase	N/A	9,150.00	9,150.00
5	3	Current Transducers 900A	Y	100.00	300.00
6	1	Assy, IGCT Matrix, 3-Phase, Line	N/A	41,008.00	41,008.00
7	1	Assy, Active Rectifier	N/A	13,474.00	13,474.00
8	1	Subpanel	N/A	4,163.40	4,163.40
9	1	Control Board	Y	1,350.00	1,350.00
10	1	Enclosure	Y	2,000.00	2,000.00
		TOTAL:			**80,064.40**

5.3.3 Line Matrix for 5.0-MW MV Turbine

The 5.0-MW line side inverter matrix is shown in Figure 4-6. The configuration is identical to the 3.0-MW system; however, note the use of two 6.6-kV symmetrical IGCTs in series. Also, in the overvoltage protection circuit, 6.6-kV diodes are in series to achieve the necessary blocking voltage capability.

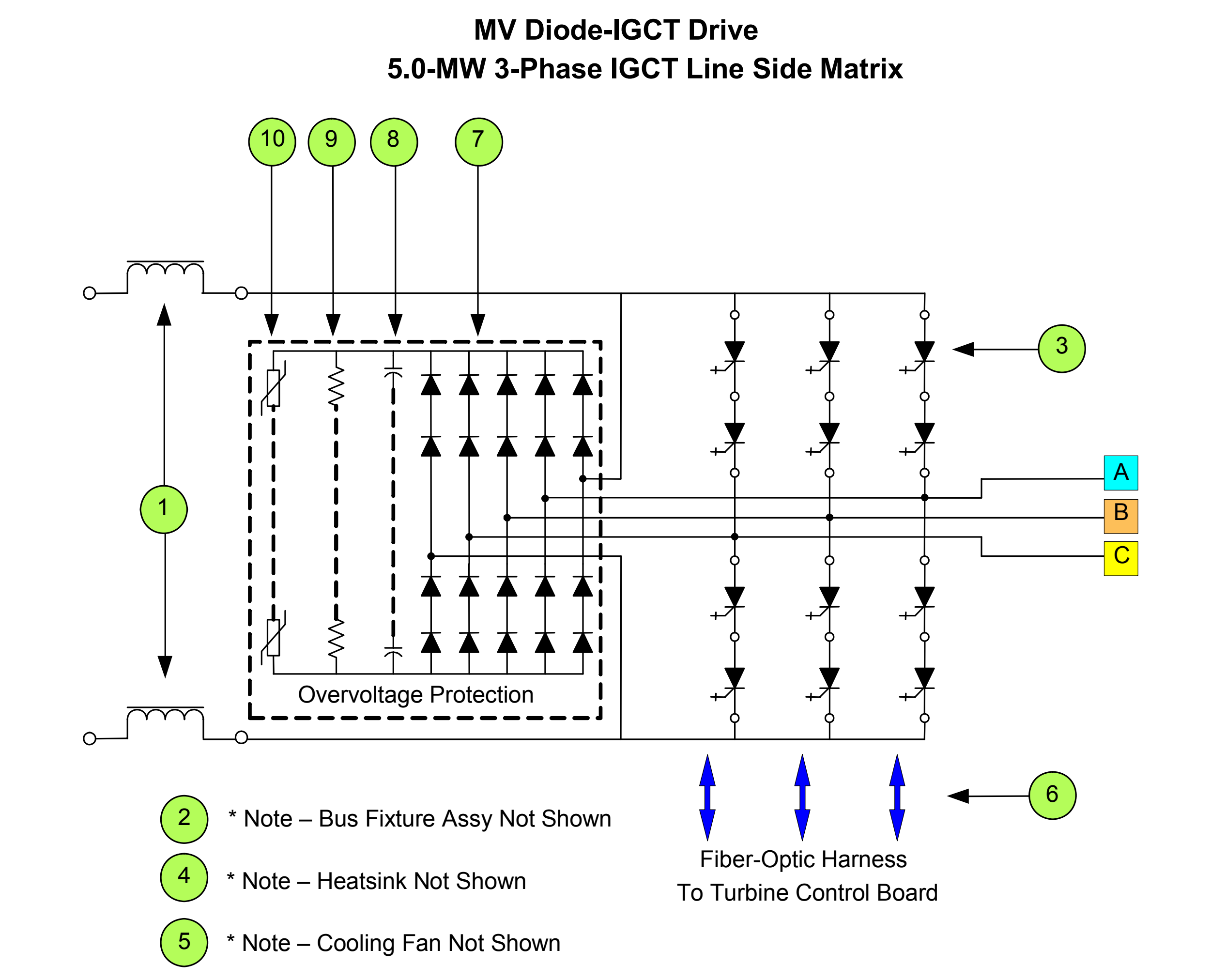


Figure 5-6 Line matrix schematic, 5.0-MW MV turbine

Table 5-11 Line matrix costing, 5.0-MW MV turbine

5.0-MW MV Diode-IGCT Matrix BOM

Item #	Qty	Description	Quoted	Unit Cost	Ext Cost
1	1	Inductor, Link, 2mH, 800A	Y	8,000.00	8,000.00
2	1	Assy, Bus Fixture	Y	500.00	500.00
3	12	IGCT, 1200A, 6600V	Y	1,800.00	21,600.00
4	1	Heatsink	Y	2,500.00	2,500.00
5	1	Cooling Fan	Y	500.00	500.00
6	1	Fiber-Optic Harness	Y	118.00	118.00
7	20	Diode, Overvoltage Protection, 6600V, 200A	Y	332.00	6,640.00
8	14	Capacitor, 8200uF, 450V Electrolytic	Y	47.00	658.00
9	14	Resistor, Balance, 10k, 25W	Y	3.00	42.00
10	6	MOV, 1000V	Y	75.00	450.00
		TOTAL:			**41,008.00**

5.3.4 Line Filter for 5.0-MW MV Turbine

The line filter for the 5.0-MW converter is costed below. A schematic is not included as the circuit is the same as in the 3.0-MW case.

Table 5-12 Line filter costing, 5.0-MW MV turbine

5.0-MW MV Diode-IGCT Filter BOM

Item #	Qty	Description	Quoted	Unit Cost	Ext Cost
1	1	Reactor, Line, 200uH, 750A, 3 Phase, 2400V	Y	4,000.00	4,000.00
2	3	Resistor, Stainless, 3 phase, 0.1 Ω/Phase	Y	500.00	1,500.00
3	1	Capacitor, 100 kVAR, 3 Phase, 7200V	Y	2,850.00	2,850.00
4	1	Enclosure	Y	800.00	800.00
		TOTAL:			**9,150.00**

5.3.5 Converter Subpanel for 5.0-MW MV Turbine

The subpanel costs in the 5.0-MW case are the same as in the 3.0-MW case.

Table 5-13 Converter subpanel costing, 5.0-MW MV turbine

5.0-MW MV Diode-IGCT Sub-Panel BOM

Item #	Qty	Description	Quoted	Unit Cost	Ext Cost
1	1	Xfmr, 3 phase Isolation, 2400:240, 5kVA	Y	1,500.00	1,500.00
2	1	Fab, Panel, Power Distribution	Y	50.00	50.00
3	1	Switch, Disconnect, 80A, 600V, 2p	Y	180.00	180.00
4	2	Circuit Breaker, 30A, 600V, 3-P	Y	120.80	241.60
5	3	Fuse, 30A, 600V	Y	5.00	15.00
6	3	Fuseblock, 100A, 600V	Y	5.00	15.00
7	2	Capacitor, Electrolytic, 300uF, 250V	Y	15.00	30.00
8	1	Assy, Harness, Main	Y	300.00	300.00
9	1	Circuit Breaker, 20A, 600V	Y	93.80	93.80
10	1	Circuit Breaker, 2A, 600V	Y	70.00	70.00
11	4	SSR, 12A, 200Vdc, MOSFET OUT	Y	17.00	68.00
12	250	350 MCM 15kV Cable	Y	5.00	1,250.00
13	1	Transformer, Control, 4kVA 1ph	Y	350.00	350.00
		TOTAL:			**4,163.40**

5.3.6 Controlled Rectifier for 5.0-MW MV Turbine

A schematic for the controlled rectifier in the 5.0-MW converter is provided below to emphasize the series device requirements in this portion of the circuit.

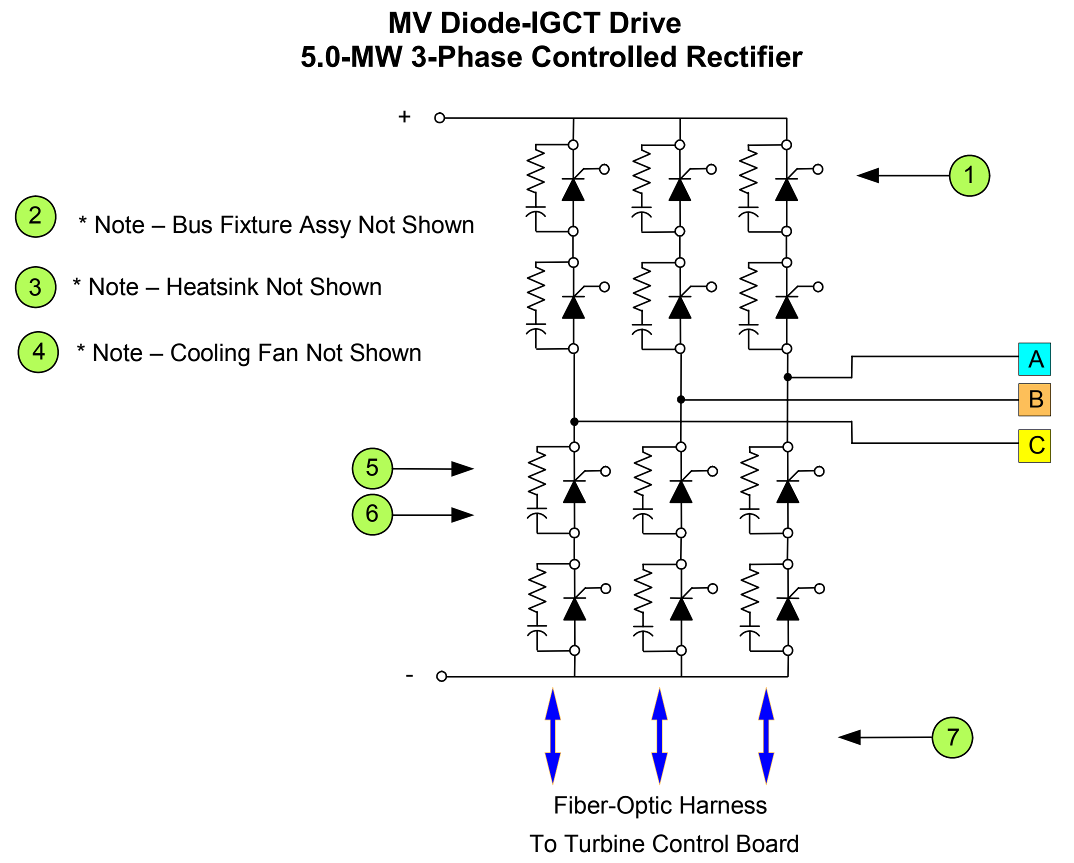


Figure 5-7 Controlled rectifier, 5.0-MW MV turbine

Table 5-14 Controlled rectifier costing, 5.0-MW MV turbine

5.0-MW MV Diode-IGCT Controlled Rectifier BOM

Item #	Qty	Description	Quoted	Unit Cost	Ext Cost
1	12	SCR, 800A, 6600V	Y	832.00	9,984.00
2	1	Bus Fixture Assy	Y	1,208.00	1,208.00
3	1	Heatsink	Y	1,604.00	1,604.00
4	1	Cooling Fan	Y	356.00	356.00
5	12	Balancing Resistor	Y	12.00	144.00
6	12	Balancing Capacitor	Y	5.00	60.00
7	1	Fiber-Optic Harness	Y	118.00	118.00
		TOTAL:			**13,474.00**

5.4 Electrical System BOM for 7.5-MW MV Turbine

Table 4-16 lists the electrical system BOM for the 7.5-MW, MV turbine. The material cost totalized at the bottom of the table will be used to compare LV and MV designs in the COE models of Section 5.

Table 5-15 7.5-MW MV electrical system BOM

#	Item	Description	Cost
1	Generator	7.5 MW, 105 Deg. C rise, 6 pole, open drip-proof, flange mounted, 33% reactance, wye connected, form wound, 97% F.L. efficiency	$ 248,312
2	Tower Pendant Cables	1285 ft. of 5/8kV shielded, 90 deg C., 500 MCM, normal stranding	$ 9,589
3	Tower Pendant Cables (festooning)	227 ft., 5/8 kV, high stranded, 500 MCM DLO	$ 1,862
4	LV Inverter	Voltage source inverter per attached included BOM's	$ 136,885
5	Transformer and Switchgear	7.5MVA, Oil filled padmount, outdoor rated, 34.5 kV primary, 6900 V wye secondary	$ 51,050
		Total Cost	$ 447,698

5.4.1 Converter System for 7.5-MW MV Turbine

Material costing for this converter is detailed below. Note that the schematics and figure, as well as subassembly BOMs, are not included in this section as they are identical to the corresponding subassemblies in the 3.0-MW converter section (both systems use 750-kW converter modules). For example, the inverter topology, the line filter, subpanel, etc. are identical to the 3.0-MW system and are costed the same.

Table 5-16 Converter system pricing spreadsheet, 7.5-MW MV turbine

7.5-MW Synchronous Machine Drive			
Direct Variable Materials (1)	$ 98,700.16	$ 98,700.16	$ 98,700.16
Direct Variable Labor (2)	$ 2,163.57	$ 2,163.57	$ 2,163.57
Direct Fixed Costs (3)	$ 1,800.00	$ 1,800.00	$ 1,800.00
Total Direct Costs	$ 102,663.73	$ 102,663.73	$ 102,663.73
Gross Margin (4)	20%	25%	30%
Sales Price	$ 128,329.67	$ 136,884.98	$ 146,662.48

(1) Annual production = 250 Turbines
(2) Includes 3% freight in
(3) Assumes 70% utilization and 30% fringe benefits
(4) Includes $120k rent, $200k capital equip, $45k utility and $85k supervision (annual costs)
(5) Gross Margin = (Sales Price - Direct Cost)/Sales Price

5.4.2 Converter Material Breakdown and BOM for 7.5-MW MV Turbine

A basic diagram and material costs of the converter main assembly are shown below, with subassembly detail shown in the subsequent four sections. Firm quotations for identified components are identified in the Quoted column.

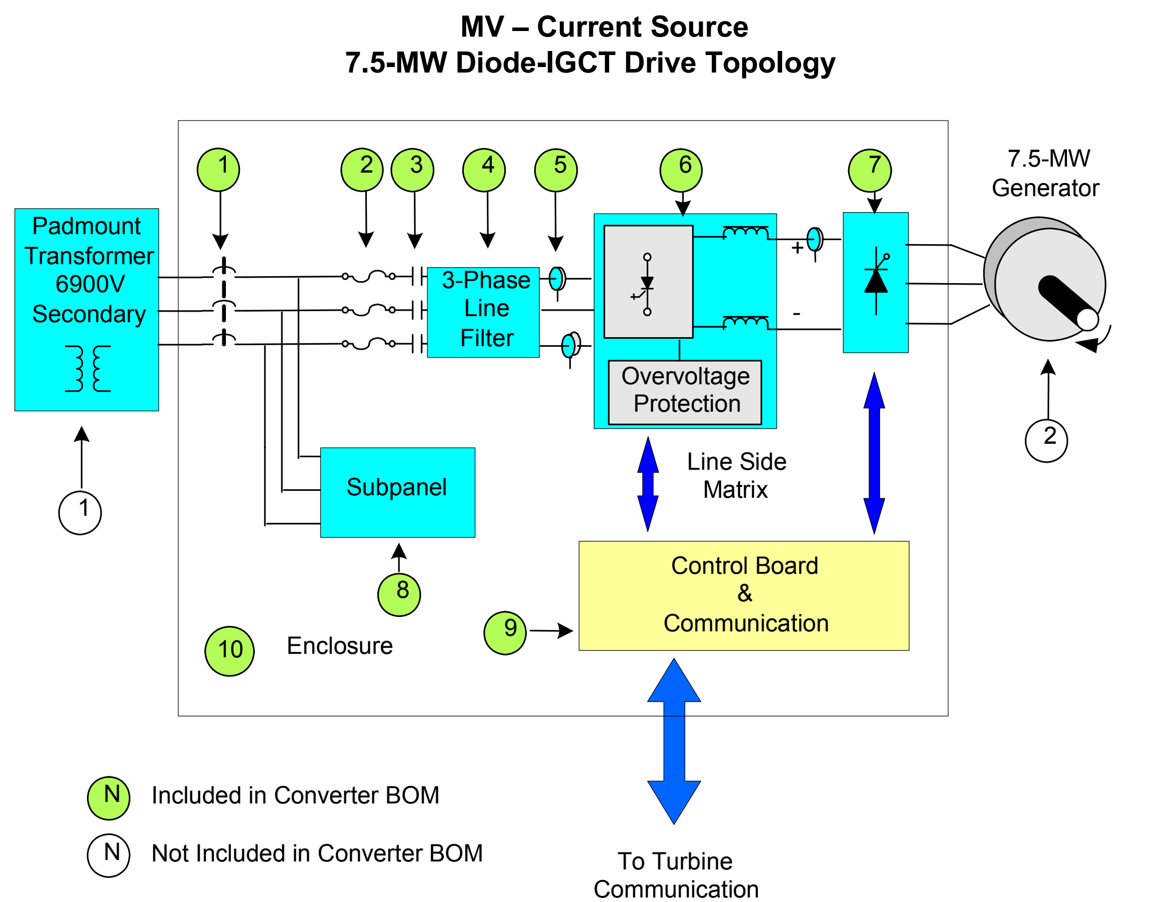


Figure 5-8 7.5-MW MV converter diagram

Table 5-17 7.5-MW MV turbine converter BOM

7.5-MW MV Diode-IGCT Converter BOM

Item #	Qty	Description	Quoted	Unit Cost	Ext Cost
1	1	Circuit Breaker, 800A, 5kVAC, 3-Pole, Line	Y	4,327.00	4,327.00
2	1	Fuse, 800A, 5kVAC, 3-Pole	Y	3,964.00	3,964.00
3	1	Contactor, 800A, 5kVAC, 3-Pole, Line	Y	4,168.00	4,168.00
4	1	Line Filter, 3 Phase	N/A	9,150.00	9,150.00
5	3	Current Transducers 900A	Y	100.00	300.00
6	1	Assy, IGCT Matrix, 3-Phase, Line	N/A	49,268.00	49,268.00
7	1	Assy, Active Rectifier	N/A	17,135.00	17,135.00
8	1	Subpanel	N/A	4,163.40	4,163.40
9	1	Control Board	Y	1,350.00	1,350.00
10	1	Enclosure	Y	2,000.00	2,000.00
		TOTAL:			**95,825.40**

5.4.3 Line Matrix for 7.5-MW MV Turbine

A schematic of the line matrix for the 7.5-MW converter system is not included here, but it is included in the 5.0-MW section of this report. The 7.5-MW system uses two series devices just as in the 5.0-MW case, but these devices are rated at 10 kV in the 7.5-MW case.

Table 5-18 Line matrix costing, 7.5-MW MV turbine

7.5-MW MV Diode-IGCT Matrix BOM

Item #	Qty	Description	Quoted	Unit Cost	Ext Cost
1	1	Inductor, Link, 2mH, 800A	Y	12,000.00	12,000.00
2	1	Assy, Bus Fixture	Y	500.00	500.00
3	12	IGCT, 1200A, 10kV	Y	1,800.00	21,600.00
4	1	Heatsink	Y	2,500.00	2,500.00
5	1	Cooling Fan	Y	500.00	500.00
6	1	Fiber-Optic Harness	Y	118.00	118.00
7	20	Diode, Overvoltage Protection, 10kV, 200A	Y	510.00	10,200.00
8	22	Capacitor, 8200uF, 450V Electrolytic	Y	47.00	1,034.00
9	22	Resistor, Balance, 10k, 25W	Y	3.00	66.00
10	10	MOV, 1000V	Y	75.00	750.00
		TOTAL:			**49,268.00**

5.4.4 Line Filter for 7.5-MW MV Turbine

The line filter schematic is the same as in the 3.0-MW and 5.0-MW cases. Costing for the 7.5-MW line filter is provided below.

Table 5-19 Line filter costing, 7.5-MW MV turbine

7.5-MW MV Diode-IGCT Filter BOM

Item #	Qty	Description	Quoted	Unit Cost	Ext Cost
1	1	Reactor, Line, 200uH, 750A, 3 Phase, 2400V	Y	4,000.00	4,000.00
2	3	Resistor, Stainless, 3 phase, 0.1 Ω/Phase	Y	500.00	1,500.00
3	1	Capacitor, 100 kVAR, 3 Phase, 7200V	Y	2,850.00	2,850.00
4	1	Enclosure	Y	800.00	800.00
		TOTAL:			**9,150.00**

5.4.5 Converter Subpanel Costing for 7.5-MW MV Turbine

The subpanel structure and cost for the 7.5-MW converter is the same as the 3.0- and 5.0-MW systems.

Table 5-20 Converter subpanel costing, 7.5-MW MV turbine

7.5-MW MV Diode-IGCT Subpanel BOM

Item #	Qty	Description	Quoted	Unit Cost	Ext Cost
1	1	Xfmr, 3 phase Isolation, 2400:240, 5kVA	Y	1,500.00	1,500.00
2	1	Fab, Panel, Power Distribution	Y	50.00	50.00
3	1	Switch, Disconnect, 80A, 600V, 2p	Y	180.00	180.00
4	2	Circuit Breaker, 30A, 600V, 3-P	Y	120.80	241.60
5	3	Fuse, 30A, 600V	Y	5.00	15.00
6	3	Fuseblock, 100A, 600V	Y	5.00	15.00
7	2	Capacitor, Electrolytic, 300uF, 250V	Y	15.00	30.00
8	1	Assy, Harness, Main	Y	300.00	300.00
9	1	Circuit Breaker, 20A, 600V	Y	93.80	93.80
10	1	Circuit Breaker, 2A, 600V	Y	70.00	70.00
11	4	SSR, 12A, 200Vdc, MOSFET OUT	Y	17.00	68.00
12	250	350 MCM 15kV Cable	Y	5.00	1,250.00
13	1	Transformer, Control, 4kVA 1ph	Y	350.00	350.00
		TOTAL:			**4,163.40**

5.4.6 Controlled Rectifier Costing for 7.5-MW MV Turbine

The 7.5-MW turbine controlled rectifier is identical to the 5.0-MW case in that it uses two series SCRs to achieve the necessary blocking voltage margin. In the 7.5-MW case, however, the devices are rated at 10 kV.

Table 5-21 Controlled rectifier costing, 7.5-MW MV turbine

7.5-MW MV Diode-IGCT Controlled Rectifier BOM

Item #	Qty	Description	Quoted	Unit Cost	Ext Cost
1	12	SCR, 800A, 10kV	Y	1,087.00	13,044.00
2	1	Bus Fixture Assy	Y	1,809.00	1,809.00
3	1	Heatsink	Y	1,604.00	1,604.00
4	1	Cooling Fan	Y	356.00	356.00
5	12	Balancing Resistor	Y	12.00	144.00
6	12	Balancing Capacitor	Y	5.00	60.00
7	1	Fiber-Optic Harness	Y	118.00	118.00
		TOTAL:			**17,135.00**

6 Comparison of COE Estimates and Conclusions

In this section, the costs of the various systems presented in this report are compared and contrasted in tabular format. The influence of the designs on annual energy production (AEP) and COE is also presented and a series of study conclusions is presented based on these specific line items, all of which summarize the studies' findings.

6.1 Cost Comparisons, AEP, and COE Estimates for the Study

Table 5.1 summarizes and contrasts the costs of the LV and MV designs discussed in this report for the 3.0-MW, 5.0-MW, and 7.5-MW turbines. Also shown in the table are Annual Energy Production (AEP) estimates for the turbines in 5.8 m/sec and 6.7 m/sec average wind speed sites. COE estimates at these wind speeds are also provided for turbines assuming the turbine design features, as presented in Section 1 of this report. Copies of the detailed COE spreadsheets are provided in Appendix A.

The baseline turbine standardized in the NREL COE calculations is based on 2002 dollars. For equivalent comparison purposes, Table 5.2 contains the same cost data as Table 5.1, adjusted to 2002 dollars. All components have been adjusted based on the U.S. Department of Labor Bureau of Labor Statistics Producer Price Index (PPI) for industrial commodities, excluding fuel, from January 2002 through January 2005. In addition, certain components have high contents of copper and steel, commodities that have experienced significantly higher price increases relative to the more general index. The costs for these materials have been adjusted using the specific PPI data for those commodities over the same time period. Appendix B contains the same COE spreadsheets provided in Appendix A but expressed in 2002 dollars

Table 6-1 Capital cost, AEP, and COE estimates (in 2005 dollars)

	3 MW			5 MW			7.5 MW		
	Low Voltage	Medium Voltage		Low Voltage	Medium Voltage		Low Voltage	Medium Voltage	
		Voltage Source	Current Source		Voltage Source	Current Source		Voltage Source	Current Source
	(575V)	(2400V)	(2400V)	(575V)	(4160V)	(4160V)	(575V)	(6900V)	(6900V)
Generator	114,000	114,000	114,000	164,000	164,000	164,000	241,000	248,312	248,312
Tower Pendant Cables (Building Wire)	18,932	7,578	7,578	48,681	7,795	7,795	74,857	9,589	9,589
Tower Pendant Cables (15% Hi-Flex Wire)	3,712	1,471	1,471	9,546	1,513	1,513	14,677	1,862	1,862
Converter	139,275	110,494	83,660	265,128	146,167	115,240	345,858	191,218	136,885
Transformer & Switchgear	34,318	34,212	34,212	45,911	41,354	41,354	62,445	51,050	51,050
TOTAL:	**310,237**	**267,755**	**240,921**	**533,266**	**360,829**	**329,902**	**738,837**	**502,031**	**447,698**
AEP MWh @ 5.8m/s	9522	9522	9522	16736	16736	16736	26360	26360	26360
AEP MWh @ 6.7m/s	11722	11722	11722	20340	20340	20340	31648	31648	31648
COE $/kWh @ 5.8m/s	0.0496	0.0490	0.0487	0.0600	0.0587	0.0585	0.0591	0.0580	0.0578
COE $/kWh @ 6.7m/s	0.0403	0.0398	0.0396	0.0494	0.0483	0.0482	0.0492	0.0483	0.0481
COE Reduction in %@5.8m/s		-1.1%	-1.8%		-2.1%	-2.4%		-1.8%	-2.2%
COE Reduction in %@6.7m/s		-1.2%	-1.7%		-2.1%	-2.4%		-1.8%	-2.2%

AEP estimates based on L.J. Fingersh, NREL/NWTC Weibul-Betz AEP worksheet, July 2004
COE estimates based on A. Laxson, NREL/NWTC COE Projection sheet, July 2004

Table 6-2 Capital cost, AEP, and COE estimates against baseline (in 2002 dollars)

	1.5 MW **Baseline**	**3 MW** Low Voltage (575V)	**3 MW** Medium Voltage Voltage Source (2400V)	**3 MW** Medium Voltage Current Source (2400V)	**5 MW** Low Voltage (575V)	**5 MW** Medium Voltage Voltage Source (4160V)	**5 MW** Medium Voltage Current Source (4160V)	**7.5 MW** Low Voltage (575V)	**7.5 MW** Medium Voltage Voltage Source (6900V)	**7.5 MW** Medium Voltage Current Source (6900V)
Generator	97,500	81,006	81,006	81,006	116,534	116,534	116,534	171,249	176,444	176,444
Tower Pendant Cables (Building Wire)	21,180	14,850	5,944	5,944	38,185	6,114	6,114	58,717	7,522	7,522
Tower Pendant Cables (15% Hi-Flex Wire)	4,140	2,912	1,154	1,154	7,488	1,187	1,187	11,513	1,461	1,461
Converter	100,500	113,447	90,259	68,640	214,920	119,052	94,134	280,161	155,411	111,573
Transformer & Switchgear	34,680	24,386	24,310	24,310	32,623	29,385	29,385	44,372	36,275	36,275
TOTAL:	**258,000**	**236,601**	**202,673**	**181,054**	**409,750**	**272,272**	**247,354**	**566,012**	**377,113**	**333,275**
AEP MWh @ 5.8m/s	4439	9522	9522	9522	16736	16736	16736	26360	26360	26360
AEP MWh @ 6.7m/s	5554	11722	11722	11722	20340	20340	20340	31648	31648	31648
COE $/kWh @ 5.8m/s	0.0482	0.0486	0.0482	0.0480	0.0591	0.0581	0.0579	0.0583	0.0574	0.0572
COE $/kWh @ 6.7m/s	0.0385	0.0395	0.0398	0.0396	0.0486	0.0478	0.0477	0.0486	0.0478	0.0477
COE Reduction vs Low Voltage										
COE Reduction in %@5.8m/s	-		0.9%	1.4%		1.7%	2.0%		1.5%	1.8%
COE Reduction in %@6.7m/s	-		-0.7%	-0.2%		1.7%	2.0%		1.5%	1.8%
COE Reduction vs Baseline										
COE Reduction in %@5.8m/s	-	-1.0%	-0.1%	0.5%	-22.6%	-20.6%	-20.2%	-21.0%	-19.2%	-18.8%
COE Reduction in %@6.7m/s	-	-2.6%	-3.3%	-2.8%	-26.3%	-24.2%	-23.8%	-26.1%	-24.2%	-23.8%

AEP estimates based on L.J. Fingersh, NREL/NWTC Weibul-Betz AEP worksheet, July 2004
COE estimates based on A. Laxson, NREL/NWTC COE Projection sheet, July 2004
Cost adjustment from 2005 to 2002 dollars based on relevant Producer Price Indices, U.S. Dept of Labor, Bureau of Labor Statistics

6.2 Summary of Conclusions

Discussion is provided below on the capital cost, AEP, and COE estimates.

6.2.1 Capital Cost Discussion

In the MV turbine class, a significant capital cost advantage goes to MV systems when compared to traditional LV systems. The 3.0-MW turbine shows a capital cost reduction of 14%, while the largest turbine, rated 7.5 MW, shows the most substantial cost reduction, approximately 40%. The average capital cost reduction of MV, voltage-source systems across this class of MW ratings is 20% compared to LV systems. MV, current-source systems show an average 33% capital cost reduction compared to the LV systems. The larger cost reductions are skewed toward larger systems, which is in line with traditional thinking.

Other considerations when examining the cost reduction levels of the MV equipment class are:

- The perceived technical risk in the development of MV converter systems is a concern to turbine manufacturers and operators. It is important to point out, however, that many of the historic technical problems have been overcome in recent years by technological advances. This includes, for example, higher-voltage power semiconductors (6.6 and 10 kV) and increased switching speeds of those semiconductors. The IGCT improvements over the GTO are a good example of the latter. Further, a rather rich and successful history of these converters in demand-side applications at the voltages and power levels discussed here exists and can be drawn upon to blunt the perceived concerns. These converters simply have not been extended to wind turbines – yet. Further, the IGCT reliability needs to be considered against that of the IGBT used in the LV design. An exhaustive study has not been performed here; however, the monolithic nature of the IGCT would normally give a significant reliability advantage to that device. However, the gate drive board for the IGCT is considerably more complex with much a larger part count and stands in stark contrast to the very simple IGBT driver. An example of a first-level reliability comparison is given in reference [2] from Section 3.

- The new ride-through requirements create a new and challenging set of issues on the converter systems. The class of voltage-source inverters inherently deals with this requirement, and the current-source inverter can be readily adapted to overcome its inherent shortcomings in this area. Also, very little history exists with either voltage-or current-source equipment meeting this type of requirement in the demand-side application mentioned above. More work is required to fully understand the performance of both voltage-source and current-source converters during periods of ride-through.

- The pendant cable line item in the capital cost section of Table 5.1 shows a substantial reduction in pendant cable costs simply due to the reduced amount of copper being used. While the MV pendant cable is quite a bit more complex in its insulation system approach than the LV cable, there is just a significantly lesser amount of total cable used in the MV systems.

- There is little difference in padmount transformer cost when moving from LV to MV systems. Different cost patterns among various manufacturers would be noticeable, but in all cases there was no significant cost difference.

6.2.2 AEP Estimates

The AEP line items in Table 5.1 show the same energy capture independent of turbine electrical system. At the rather high level of analysis used in this study, no compelling improvement in system efficiency was found to exist at medium voltage. The converter efficiency was about the same in LV and MV converters, generators, pendant cables, and transformer efficiency data were essentially the same. Small advantages were offset by disadvantages elsewhere. A more detailed analysis may reveal an advantage to one system or the other, but if it could be found, it is expected to be quite small with no meaningful positive impact on energy capture. These comments are not to be confused with increasing energy efficiency on all of the described systems, which is achievable (but at an increased capital cost).

6.2.3 COE Estimates

A number of important points must be made relative to the COE line item in Table 5.1.

- MV systems show a reduction in the COE ranging from about 1.2% to 2.5% over comparable LV systems. However, the absolute COE line item in the table should be viewed with some uncertainty. During the study period (approximately 9 months), commodity prices increased substantially, and cost-scaling relationships used in non-electrical system components became quite volatile. On the electrical side, the components most affected by commodity prices are the generator, pendant cables, and transformers. Present, accurate costing is included for these line items, but their costs are higher than those used at the beginning of the study because of inflationary commodity pressures. These inflationary pressures also put the baseline 1.5-MW machine capital cost and COE in question at this time as this machine was added to the model some time ago. Converter system cost increases have been mostly unaffected by commodity prices, but where they exist, these are included in the costing as shown.

- The COE estimates include installation line items, which are dominated by mechanical erection and foundation costs. A small component of this line item involves electrical interconnect, however. One expressed concern with MV equipment is that costs associated with these activities would rise due to increased skill level and personnel wages. This is a very complex question involving many factors. To look at this in a tractable way, a simple pendant cable termination analysis was performed. The details for this analysis are included in Appendix B. The comparison involves large number of simple, low-cost, LV terminations versus a small number of higher-cost complex terminations. The analysis in the Appendix shows that at 3.0 MW, there is no clear advantage in the termination installation costs. At 7.5 MW however, the difference increases quite a bit, but really not in a way that would drive COE. Recall that the way voltages were selected, leading to the same size and number of MV cables, the termination of MV systems is the same at 3.0, 5.0, and 7.5 MW.

- Maintenance cost is more difficult to analyze than installation cost. Clearly the required skill level increases for the electricians working on the equipment, and an approximate 10% – 12 % wage adder goes with it (see Section 1). However, a reliability analysis (not performed in this study) would likely reveal that because of significantly reduced part count over LV equipment, reliability should increase and unscheduled turbine visits should decrease. In the extreme, however, without reliability enhancement, the labor content of electrical maintenance in most turbine maintenance models is so small that a 10% – 12% increase and even a 100% increase due to two-men crews still has very little impact on the maintenance line item and therefore COE. In other words, the majority of the maintenance costs have nothing to do with electrical issues driven by MV or LV operation.

- A comparison of MV turbines against the 2002 Baseline 1.5-MW turbine is also provided in Table 5.2. This table incorporates the results from this study with 2002 costing levels to offset the recent run-up in commodity prices. Two rows at the bottom compare low voltage to medium, which show the favorable effects of the MV apparatus. The bottom rows are a comparison against the baseline turbine, and these are shown unfavorable with regard to COE, owing entirely to the simple scaling laws applied to the size and cost of non-electrical components (i.e., the rotor, tower, foundation and other structural/mechanical components). Other NREL studies have described this, and when designs are completed and move past the simple scaling laws, COE's have historically gone down. This same phenomenon is expected to occur here in the event that a thorough design process would be followed. A further complication involves the doubly fed system used in the baseline. It would not meet the new stringent ride-through requirements as discussed in this study, making an exact comparison difficult.

Appendix C provides an application specification developed to solicit data and feedback from manufacturers and vendors.

Appendix A COE Details Using 2005 Dollars for Components Included within Study

The following three tables detail capital cost, operation and maintenance costs, annual energy production, and COE for three configurations:

- Low Voltage, Voltage Source
- Medium Voltage, Voltage Source
- Medium Voltage, Current Source.

In this Appendix, components included in this study were costed in 2005 dollars.

Costs for non-electrical components not directly sized and costed in this study were scaled from the *WindPACT Turbine Rotor Design Study June 2000 – June 2002* (Malcolm, D.J., and Hansen, A.C. National Renewable Energy Laboratory, NREL/SR-500-32495, August 2002).

LOW-VOLTAGE VOLTAGE-SOURCE

Turbine Rating (kW)	1500	3000		5000		7500	
Component	Baseline Component Costs $1000	Projected Component Costs $1000	Component Normalized % Improvement	Projected Component Costs $1000	Component Normalized % Improvement	Projected Component Costs $1000	Component Normalized % Improvement
Rotor	**248**	**727**	46.9%	**1,484**	79.9%	**2,356**	90.4%
Blades	148	437	47.8%	906	83.9%	1,440	94.9%
Hub	64	213	65.9%	429	100.5%	688	114.4%
Pitch mechanism & bearings	36	77	8.3%	149	25.7%	228	28.3%
Drive train,nacelle	**563**	**1,077**	-4.3%	**2,151**	14.7%	**3,272**	16.3%
Low speed shaft	20	56	41.0%	121	82.8%	192	93.4%
Bearings	12	41	66.4%	102	148.4%	164	166.3%
Gearbox	151	357	18.3%	697	38.6%	1,081	43.3%
Mech brake, HS cpling etc	3	6	0.5%	10	0.5%	15	0.5%
Generator	98	114	-41.5%	164	-49.5%	241	-50.6%
Variable spd electronics	101	141	-29.9%	267	-20.4%	348	-30.8%
Yaw drive & bearing	12	28	15.8%	110	172.9%	174	187.8%
Main frame	64	192	50.0%	434	103.5%	692	116.3%
Electrical connections	60	57	-52.5%	104	-47.9%	152	-49.3%
Hydraulic system	7	14	3.7%	23	2.2%	35	3.7%
Nacelle cover	36	71	-1.1%	119	-0.6%	178	-0.8%
Control, safety system	**10**	**10**	-50.0%	**11**	-67.0%	**12**	-76.0%
Tower	**101**	**303**	50.0%	**647**	92.1%	**1,030**	104.0%
TURBINE CAPITAL COST (TCC)	**921**	**2,117**	14.9%	**4,293**	39.8%	**6,670**	44.8%
Foundations	49	58	-40.2%	108	-33.2%	147	-39.4%
Transportation	51	253	148.0%	1,312	671.7%	2,140	739.2%
Roads, civil works	79	136	-13.8%	255	-3.1%	377	-4.5%
Assembly & installation	51	113	11.4%	225	33.1%	347	36.8%
Elect interfc/connect	127	224	-11.5%	432	2.4%	643	1.6%
Permits, engineering	33	70	7.0%	127	16.5%	194	18.7%
BALANCE OF STATION COST (BOS)	**388**	**854**	9.9%	**2,459**	89.9%	**3,848**	98.1%
Project Uncertainty	**162**	**324**	0.0%	**540**	0.0%	**810**	0.0%
Initial Capital Cost (ICC)	**1,472**	**3,295**	11.9%	**7,292**	48.6%	**11,328**	53.9%
Installed Cost per kW	**981**	**1,098**	11.9%	**1,458**	48.6%	**1,510**	-69.2%
Turbine Capital per kW sans BOS	**690**	**783**	13.4%	**927**	34.3%	**958**	-72.2%
LEVELIZED REPLACEMENT COSTS (LRC) ($10.70/kW)	16	32	0.0%	54	0.0%	80	0.0%
O&M, 5.8 m/s site ($0.007/kWh)	31	67	7.3%	117	13.1%	185	18.8%
O&M, 6.7 m/s site ($0.007/kWh)	39	82	5.5%	142	9.9%	222	14.0%
Land ($3.20/kW)	5	10	0.0%	16	0.0%	24	0.0%
NET 5.8 m/s ANNUAL ENERGY PRODUCTION MWh (AEP)	4439	9522		16736		26360	
Net 6.7 m/s ANNUAL ENERGY PRODUCTION Energy MWh (AEP)	5554	11722		20340		31648	
Fixed Charge Rate	11.85%	11.85%		11.85%		11.85%	
COE at 5.8 m/s $/kWh	**0.0482**	**0.0496**	2.9%	**0.0600**	24.5%	**0.0591**	22.6%
COE at 6.7 m/s $/kWh	**0.0385**	**0.0403**	4.6%	**0.0494**	28.2%	**0.0492**	27.8%

MEDIUM-VOLTAGE VOLTAGE-SOURCE

Turbine Rating (kW)	1500	3000		5000		7500	
Component	Baseline Component Costs $1000	Projected Component Costs $1000	Component Normalized % Improvement	Projected Component Costs $1000	Component Normalized % Improvement	Projected Component Costs $1000	Component Normalized % Improvement
Rotor	**248**	**727**	46.9%	**1,484**	79.9%	**2,356**	90.4%
Blades	148	437	47.8%	906	83.9%	1,440	94.9%
Hub	64	213	65.9%	429	100.5%	688	114.4%
Pitch mechanism & bearings	36	77	8.3%	149	25.7%	228	28.3%
Drive train,nacelle	**563**	**1,034**	-8.1%	**1,978**	5.5%	**3,035**	7.8%
Low speed shaft	20	56	41.0%	121	82.8%	192	93.4%
Bearings	12	41	66.4%	102	148.4%	164	166.3%
Gearbox	151	357	18.3%	697	38.6%	1,081	43.3%
Mech brake, HS cpling etc	3	6	0.5%	10	0.5%	15	0.5%
Generator	98	114	-41.5%	164	-49.5%	248	-49.1%
Variable spd electronics	101	112	-44.3%	148	-55.9%	193	-61.6%
Yaw drive & bearing	12	28	15.8%	110	172.9%	174	187.8%
Main frame	64	192	50.0%	434	103.5%	692	116.3%
Electrical connections	60	43	-63.9%	51	-74.7%	63	-79.2%
Hydraulic system	7	14	3.7%	23	2.2%	35	3.7%
Nacelle cover	36	71	-1.1%	119	-0.6%	178	-0.8%
Control, safety system	**10**	**10**	-50.0%	**11**	-67.0%	**12**	-76.0%
Tower	**101**	**303**	50.0%	**647**	92.1%	**1,030**	104.0%
TURBINE CAPITAL COST (TCC)	**921**	**2,074**	12.6%	**4,120**	34.2%	**6,433**	39.6%
Foundations	49	58	-40.2%	108	-33.2%	147	-39.4%
Transportation	51	253	148.0%	1,312	671.7%	2,140	739.2%
Roads, civil works	79	136	-13.8%	255	-3.1%	377	-4.5%
Assembly & installation	51	113	11.4%	225	33.1%	347	36.8%
Elect interfc/connect	127	224	-11.7%	430	2.0%	641	1.3%
Permits, engineering	33	70	7.0%	127	16.5%	194	18.7%
BALANCE OF STATION COST (BOS)	**388**	**854**	9.9%	**2,457**	89.8%	**3,846**	98.0%
Project Uncertainty	**162**	**324**	0.0%	**540**	0.0%	**810**	0.0%
Initial Capital Cost (ICC)	**1,472**	**3,252**	10.5%	**7,118**	45.1%	**11,089**	50.7%
Installed Cost per kW	**981**	**1,084**	10.5%	**1,424**	45.1%	**1,478**	-69.9%
Turbine Capital per kW sans BOS	**690**	**768**	11.3%	**892**	29.2%	**925**	-73.2%
LEVELIZED REPLACEMENT COSTS (LRC) ($10.70/kW)	16	32	0.0%	54	0.0%	80	0.0%
O&M, 5.8 m/s site ($0.007/kWh)	31	67	7.3%	117	13.1%	185	18.8%
O&M, 6.7 m/s site ($0.007/kWh)	39	82	5.5%	142	9.9%	222	14.0%
Land ($3.20/kW)	5	10	0.0%	16	0.0%	24	0.0%
NET 5.8 m/s ANNUAL ENERGY PRODUCTION MWh (AEP)	4439	9522		16736		26360	
Net 6.7 m/s ANNUAL ENERGY PRODUCTION Energy MWh (AEP)	5554	11722		20340		31648	
Fixed Charge Rate	11.85%	11.85%		11.85%		11.85%	
COE at 5.8 m/s $/kWh	**0.0482**	**0.0490**	1.8%	**0.0587**	21.9%	**0.0580**	20.4%
COE at 6.7 m/s $/kWh	**0.0385**	**0.0398**	3.5%	**0.0483**	25.5%	**0.0483**	25.4%

MEDIUM-VOLTAGE CURRENT-SOURCE

Turbine Rating (kW)	1500	3000		5000		7500	
Component	Baseline Component Costs $1000	Projected Component Costs $1000	Component Normalized % Improvement	Projected Component Costs $1000	Component Normalized % Improvement	Projected Component Costs $1000	Component Normalized % Improvement
Rotor	**248**	**727**	46.9%	**1,484**	79.9%	**2,356**	90.4%
Blades	148	437	47.8%	906	83.9%	1,440	94.9%
Hub	64	213	65.9%	429	100.5%	688	114.4%
Pitch mechanism & bearings	36	77	8.3%	149	25.7%	228	28.3%
Drive train,nacelle	**563**	**1,007**	-10.5%	**1,948**	3.8%	**2,980**	5.9%
Low speed shaft	20	56	41.0%	121	82.8%	192	93.4%
Bearings	12	41	66.4%	102	148.4%	164	166.3%
Gearbox	151	357	18.3%	697	38.6%	1,081	43.3%
Mech brake, HS cpling etc	3	6	0.5%	10	0.5%	15	0.5%
Generator	98	114	-41.5%	164	-49.5%	248	-49.1%
Variable spd electronics	101	85	-57.6%	117	-65.1%	138	-72.4%
Yaw drive & bearing	12	28	15.8%	110	172.9%	174	187.8%
Main frame	64	192	50.0%	434	103.5%	692	116.3%
Electrical connections	60	43	-63.9%	51	-74.7%	63	-79.2%
Hydraulic system	7	14	3.7%	23	2.2%	35	3.7%
Nacelle cover	36	71	-1.1%	119	-0.6%	178	-0.8%
Control, safety system	**10**	**10**	-50.0%	**11**	-67.0%	**12**	-76.0%
Tower	**101**	**303**	50.0%	**647**	92.1%	**1,030**	104.0%
TURBINE CAPITAL COST (TCC)	**921**	**2,048**	11.1%	**4,089**	33.2%	**6,378**	38.5%
Foundations	49	58	-40.2%	108	-33.2%	147	-39.4%
Transportation	51	253	148.0%	1,312	671.7%	2,140	739.2%
Roads, civil works	79	136	-13.8%	255	-3.1%	377	-4.5%
Assembly & installation	51	113	11.4%	225	33.1%	347	36.8%
Elect interfc/connect	127	224	-11.7%	430	2.0%	641	1.3%
Permits, engineering	33	70	7.0%	127	16.5%	194	18.7%
BALANCE OF STATION COST (BOS)	**388**	**854**	9.9%	**2,457**	89.8%	**3,846**	98.0%
Project Uncertainty	**162**	**324**	0.0%	**540**	0.0%	**810**	0.0%
Initial Capital Cost (ICC)	**1,472**	**3,225**	9.6%	**7,087**	44.5%	**11,034**	50.0%
Installed Cost per kW	**981**	**1,075**	9.6%	**1,417**	44.5%	**1,471**	-70.0%
Turbine Capital per kW sans BOS	**690**	**759**	9.9%	**885**	28.3%	**918**	-73.4%
LEVELIZED REPLACEMENT COSTS (LRC) ($10.70/kW)	16	32	0.0%	54	0.0%	80	0.0%
O&M, 5.8 m/s site ($0.007/kWh)	31	67	7.3%	117	13.1%	185	18.8%
O&M, 6.7 m/s site ($0.007/kWh)	39	82	5.5%	142	9.9%	222	14.0%
Land ($3.20/kW)	5	10	0.0%	16	0.0%	24	0.0%
NET 5.8 m/s ANNUAL ENERGY PRODUCTION MWh (AEP)	4439	9522		16736		26360	
Net 6.7 m/s ANNUAL ENERGY PRODUCTION Energy MWh (AEP)	5554	11722		20340		31648	
Fixed Charge Rate	11.85%	11.85%		11.85%		11.85%	
COE at 5.8 m/s $/kWh	**0.0482**	**0.0487**	1.1%	**0.0585**	21.5%	**0.0578**	19.9%
COE at 6.7 m/s $/kWh	**0.0385**	**0.0396**	2.8%	**0.0482**	25.1%	**0.0481**	24.9%

Appendix B COE Details Using 2002 Dollars for Components Included within Study

The following three tables detail capital cost, operation and maintenance costs, annual energy production, and COE for three configurations:

- Low Voltage, Voltage Source
- Medium Voltage, Voltage Source
- Medium Voltage, Current Source.

In this Appendix, components included in this study were costed in 2002 dollars. Costs are adjusted according to the rules stated in Table 5-2.

Costs for non-electrical components not directly sized and costed in this study were scaled from the *WindPACT Turbine Rotor Design Study June 2000 – June 2002 (*Malcolm, D.J., and Hansen, A.C. National Renewable Energy Laboratory, NREL/SR-500-32495, August 2002).

LOW-VOLTAGE VOLTAGE-SOURCE

Turbine Rating (kW)	1500	3000		5000		7500	
Component	Baseline Component Costs $1000	Projected Component Costs $1000	Component Normalized % Improvement	Projected Component Costs $1000	Component Normalized % Improvement	Projected Component Costs $1000	Component Normalized % Improvement
Rotor	**248**	**727**	46.9%	**1,484**	79.9%	**2,356**	90.4%
Blades	148	437	47.8%	906	83.9%	1,440	94.9%
Hub	64	213	65.9%	429	100.5%	688	114.4%
Pitch mechanism & bearings	36	77	8.3%	149	25.7%	228	28.3%
Drive train,nacelle	**563**	**1,002**	-11.0%	**2,026**	8.0%	**3,097**	10.1%
Low speed shaft	20	56	41.0%	121	82.8%	192	93.4%
Bearings	12	41	66.4%	102	148.4%	164	166.3%
Gearbox	151	357	18.3%	697	38.6%	1,081	43.3%
Mech brake, HS cpling etc	3	6	0.5%	10	0.5%	15	0.5%
Generator	98	81	-58.5%	117	-64.1%	171	-64.9%
Variable spd electronics	101	113	-43.6%	215	-35.8%	280	-44.2%
Yaw drive & bearing	12	28	15.8%	110	172.9%	174	187.8%
Main frame	64	192	50.0%	434	103.5%	692	116.3%
Electrical connections	60	42	-64.9%	78	-60.9%	115	-61.8%
Hydraulic system	7	14	3.7%	23	2.2%	35	3.7%
Nacelle cover	36	71	-1.1%	119	-0.6%	178	-0.8%
Control, safety system	**10**	**10**	-50.0%	**11**	-67.0%	**12**	-76.0%
Tower	**101**	**303**	50.0%	**647**	92.1%	**1,030**	104.0%
TURBINE CAPITAL COST (TCC)	**921**	**2,042**	10.8%	**4,168**	35.7%	**6,495**	41.0%
Foundations	49	58	-40.2%	108	-33.2%	147	-39.4%
Transportation	51	253	148.0%	1,312	671.7%	2,140	739.2%
Roads, civil works	79	136	-13.8%	255	-3.1%	377	-4.5%
Assembly & installation	51	113	11.4%	225	33.1%	347	36.8%
Elect interfc/connect	127	224	-11.5%	432	2.4%	643	1.6%
Permits, engineering	33	70	7.0%	127	16.5%	194	18.7%
BALANCE OF STATION COST (BOS)	**388**	**854**	9.9%	**2,459**	89.9%	**3,848**	98.1%
Project Uncertainty	**162**	**324**	0.0%	**540**	0.0%	**810**	0.0%
Initial Capital Cost (ICC)	**1,472**	**3,220**	9.4%	**7,167**	46.1%	**11,153**	51.6%
Installed Cost per kW	**981**	**1,073**	9.4%	**1,433**	46.1%	**1,487**	-69.7%
Turbine Capital per kW sans BOS	**690**	**757**	9.6%	**901**	30.6%	**934**	-72.9%
LEVELIZED REPLACEMENT COSTS (LRC) ($10.70/kW)	16	32	0.0%	54	0.0%	80	0.0%
O&M, 5.8 m/s site ($0.007/kWh)	31	67	7.3%	117	13.1%	185	18.8%
O&M, 6.7 m/s site ($0.007/kWh)	39	82	5.5%	142	9.9%	222	14.0%
Land ($3.20/kW)	5	10	0.0%	16	0.0%	24	0.0%
NET 5.8 m/s ANNUAL ENERGY PRODUCTION MWh (AEP)	4439	9522		16736		26360	
Net 6.7 m/s ANNUAL ENERGY PRODUCTION Energy MWh (AEP)	5554	11722		20340		31648	
Fixed Charge Rate	11.85%	11.85%		11.85%		11.85%	
COE at 5.8 m/s $/kWh	**0.0482**	**0.0486**	1.0%	**0.0591**	22.6%	**0.0583**	21.0%
COE at 6.7 m/s $/kWh	**0.0385**	**0.0395**	2.6%	**0.0486**	26.3%	**0.0486**	26.1%

MEDIUM-VOLTAGE VOLTAGE-SOURCE

Turbine Rating (kW)	1500	3000		5000		7500	
Component	Baseline Component Costs $1000	Projected Component Costs $1000	Component Normalized % Improvement	Projected Component Costs $1000	Component Normalized % Improvement	Projected Component Costs $1000	Component Normalized % Improvement
Rotor	**248**	**727**	46.9%	**1,484**	79.9%	**2,356**	90.4%
Blades	148	437	47.8%	906	83.9%	1,440	94.9%
Hub	64	213	65.9%	429	100.5%	688	114.4%
Pitch mechanism & bearings	36	77	8.3%	149	25.7%	228	28.3%
Drive train,nacelle	**563**	**968**	-14.0%	**1,888**	0.7%	**2,908**	3.3%
Low speed shaft	20	56	41.0%	121	82.8%	192	93.4%
Bearings	12	41	66.4%	102	148.4%	164	166.3%
Gearbox	151	357	18.3%	697	38.6%	1,081	43.3%
Mech brake, HS cpling etc	3	6	0.5%	10	0.5%	15	0.5%
Generator	98	81	-58.5%	117	-64.1%	176	-63.8%
Variable spd electronics	101	90	-55.1%	119	-64.5%	155	-69.1%
Yaw drive & bearing	12	28	15.8%	110	172.9%	174	187.8%
Main frame	64	192	50.0%	434	103.5%	692	116.3%
Electrical connections	60	31	-73.8%	37	-81.7%	45	-84.9%
Hydraulic system	7	14	3.7%	23	2.2%	35	3.7%
Nacelle cover	36	71	-1.1%	119	-0.6%	178	-0.8%
Control, safety system	**10**	**10**	-50.0%	**11**	-67.0%	**12**	-76.0%
Tower	**101**	**303**	50.0%	**647**	92.1%	**1,030**	104.0%
TURBINE CAPITAL COST (TCC)	**921**	**2,008**	9.0%	**4,030**	31.2%	**6,306**	36.9%
Foundations	49	58	-40.2%	108	-33.2%	147	-39.4%
Transportation	51	253	148.0%	1,312	671.7%	2,140	739.2%
Roads, civil works	79	136	-13.8%	255	-3.1%	377	-4.5%
Assembly & installation	51	113	11.4%	225	33.1%	347	36.8%
Elect interfc/connect	127	224	-11.7%	430	2.0%	641	1.3%
Permits, engineering	33	70	7.0%	127	16.5%	194	18.7%
BALANCE OF STATION COST (BOS)	**388**	**854**	9.9%	**2,457**	89.8%	**3,846**	98.0%
Project Uncertainty	**162**	**324**	0.0%	**540**	0.0%	**810**	0.0%
Initial Capital Cost (ICC)	**1,472**	**3,185**	8.2%	**7,028**	43.3%	**10,962**	49.0%
Installed Cost per kW	**981**	**1,062**	8.2%	**1,406**	43.3%	**1,462**	-70.2%
Turbine Capital per kW sans BOS	**690**	**745**	7.9%	**873**	26.5%	**908**	-73.7%
LEVELIZED REPLACEMENT COSTS (LRC) ($10.70/kW)	16	32	0.0%	54	0.0%	80	0.0%
O&M, 5.8 m/s site ($0.007/kWh)	31	67	7.3%	117	13.1%	185	18.8%
O&M, 6.7 m/s site ($0.007/kWh)	39	82	5.5%	142	9.9%	222	14.0%
Land ($3.20/kW)	5	10	0.0%	16	0.0%	24	0.0%
NET 5.8 m/s ANNUAL ENERGY PRODUCTION MWh (AEP)	4439	9522		16736		26360	
Net 6.7 m/s ANNUAL ENERGY PRODUCTION Energy MWh (AEP)	5554	11722		20340		31648	
Fixed Charge Rate	11.85%	11.85%		11.85%		11.85%	
COE at 5.8 m/s $/kWh	**0.0482**	**0.0482**	0.1%	**0.0581**	20.6%	**0.0574**	19.2%
COE at 6.7 m/s $/kWh	**0.0385**	**0.0392**	1.7%	**0.0478**	24.2%	**0.0478**	24.2%

MEDIUM-VOLTAGE CURRENT-SOURCE

Turbine Rating (kW)	1500	3000		5000		7500	
Component	Baseline Component Costs $1000	Projected Component Costs $1000	Component Normalized % Improvement	Projected Component Costs $1000	Component Normalized % Improvement	Projected Component Costs $1000	Component Normalized % Improvement
Rotor	**248**	**727**	46.9%	**1,484**	79.9%	**2,356**	90.4%
Blades	148	437	47.8%	906	83.9%	1,440	94.9%
Hub	64	213	65.9%	429	100.5%	688	114.4%
Pitch mechanism & bearings	36	77	8.3%	149	25.7%	228	28.3%
Drive train,nacelle	**563**	**946**	-15.9%	**1,863**	-0.7%	**2,864**	1.8%
Low speed shaft	20	56	41.0%	121	82.8%	192	93.4%
Bearings	12	41	66.4%	102	148.4%	164	166.3%
Gearbox	151	357	18.3%	697	38.6%	1,081	43.3%
Mech brake, HS cpling etc	3	6	0.5%	10	0.5%	15	0.5%
Generator	98	81	-58.5%	117	-64.1%	176	-63.8%
Variable spd electronics	101	69	-65.9%	94	-71.9%	112	-77.8%
Yaw drive & bearing	12	28	15.8%	110	172.9%	174	187.8%
Main frame	64	192	50.0%	434	103.5%	692	116.3%
Electrical connections	60	31	-73.8%	37	-81.7%	45	-84.9%
Hydraulic system	7	14	3.7%	23	2.2%	35	3.7%
Nacelle cover	36	71	-1.1%	119	-0.6%	178	-0.8%
Control, safety system	**10**	**10**	-50.0%	**11**	-67.0%	**12**	-76.0%
Tower	**101**	**303**	50.0%	**647**	92.1%	**1,030**	104.0%
TURBINE CAPITAL COST (TCC)	**921**	**1,986**	7.8%	**4,005**	30.4%	**6,262**	35.9%
Foundations	49	58	-40.2%	108	-33.2%	147	-39.4%
Transportation	51	253	148.0%	1,312	671.7%	2,140	739.2%
Roads, civil works	79	136	-13.8%	255	-3.1%	377	-4.5%
Assembly & installation	51	113	11.4%	225	33.1%	347	36.8%
Elect interfc/connect	127	224	-11.7%	430	2.0%	641	1.3%
Permits, engineering	33	70	7.0%	127	16.5%	194	18.7%
BALANCE OF STATION COST (BOS)	**388**	**854**	9.9%	**2,457**	89.8%	**3,846**	98.0%
Project Uncertainty	**162**	**324**	0.0%	**540**	0.0%	**810**	0.0%
Initial Capital Cost (ICC)	**1,472**	**3,164**	7.5%	**7,003**	42.7%	**10,918**	48.4%
Installed Cost per kW	**981**	**1,055**	7.5%	**1,401**	42.7%	**1,456**	-70.3%
Turbine Capital per kW sans BOS	**690**	**738**	6.9%	**868**	25.8%	**902**	-73.9%
LEVELIZED REPLACEMENT COSTS (LRC) ($10.70/kW)	16	32	0.0%	54	0.0%	80	0.0%
O&M, 5.8 m/s site ($0.007/kWh)	31	67	7.3%	117	13.1%	185	18.8%
O&M, 6.7 m/s site ($0.007/kWh)	39	82	5.5%	142	9.9%	222	14.0%
Land ($3.20/kW)	5	10	0.0%	16	0.0%	24	0.0%
NET 5.8 m/s ANNUAL ENERGY PRODUCTION MWh (AEP)	4439	9522		16736		26360	
Net 6.7 m/s ANNUAL ENERGY PRODUCTION Energy MWh (AEP)	5554	11722		20340		31648	
Fixed Charge Rate	11.85%	11.85%		11.85%		11.85%	
COE at 5.8 m/s $/kWh	**0.0482**	**0.0480**	-0.5%	**0.0579**	20.2%	**0.0572**	18.8%
COE at 6.7 m/s $/kWh	**0.0385**	**0.0390**	1.1%	**0.0477**	23.8%	**0.0477**	23.8%

Appendix C Cable Termination Study

The following table provides a simple analysis highlighting cable termination activities for LV and MV systems. The results of this study were then used in the installation cost calculations.

Cable Termination & Connection:	3 MW			5 MW			7.5 MW		
	Low Voltage (575V)	Medium Voltage Voltage Source (2400V)	Medium Voltage Current Source (2400V)	Low Voltage (575V)	Medium Voltage Voltage Source (4160V)	Medium Voltage Current Source (4160V)	Low Voltage (575V)	Medium Voltage Voltage Source (6900V)	Medium Voltage Current Source (6900V)
# Cables	36.00	9.00	9.00	72.00	9.00	9.00	90.00	9.00	9.00
# Terminations	72.00	18.00	18.00	144.00	18.00	18.00	180.00	18.00	18.00
LV Electrician Rate ($/hr)	60.00			60.00			60.00		
LV Termination Time per Lug (hrs)	0.25			0.25			0.25		
Labor $ / Termination	15.00			15.00			15.00		
MV Electrician Rate		70.00	70.00		70.00	70.00		70.00	70.00
MV Termination Time per Lug		0.50	0.50		0.50	0.50		0.50	0.50
Labor $ / Termination		35.00	35.00		35.00	35.00		35.00	35.00
Total Termination & Connection Cost ($)	1080.00	630.00	630.00	2160.00	630.00	630.00	2700.00	630.00	630.00

Appendix D Application Specification

The attached report provides an application specification developed to solicit data and feedback from manufacturers and vendors.

Medium Voltage Electrical Drive System for Variable Speed Wind Turbines

Application Specification

Revision 3
April 1, 2005

Prepared by:

William L. Erdman, Ph.D.
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Change Tracking

Revision	Date	Reasons for Changes	Paragraphs Affected
0	9/1/04	Initial Draft – North America (4.16 kV)	
1	11/2/04	Change power ratings to 3, 5 and 7.5 MW; add E.ON Netz requirements; add generator construction details;	1.0, 2.0, 5.1-5.16,
2	11/23/04	Add voltage source inverter option	3.0, 8.0, 8.8.4
3	4/1/05	Revised to reflect new voltage ratings and relocation of rectifier from nacelle to down tower	5.11, 6.0, 6.5, 7.2, 7.3, 8.4, 8.4, 9.2, 10.4, 10.13

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Tables

Figures

1.0 Scope and Purpose

The purpose of this document is to define application requirements for a medium voltage drive train to be utilized for reduced COE from low wind speed multi-megawatt wind turbines. These application requirements establish design criteria by which cost and performance data may be estimated.

The scope of this document is limited to the electrical drive train components consisting of a single synchronous generator, a rectifier assembly, DC power distribution from the nacelle to the tower base, an inverter assembly, and AC power distribution from the inverter to a transformer/switchgear assembly located external to the turbine tower, as shown in Figure 1, below.

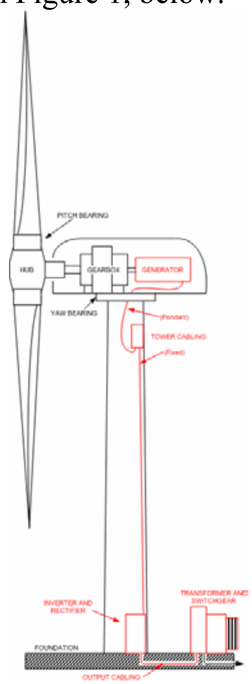

Figure 1. Scope of Specification

The rotor, hub, gearbox, main and high speed shafts, pitch and yaw systems and tower are specifically excluded from the scope of this document. However, certain assumptions about these components are necessary in order to fully specify the electrical system. It has been assumed the generator is driven by a two-stage gearbox to provide a speed range of approximately 600 to 1440 rpm for the generator. With regard to tower height, which greatly impacts DC power cable costs, it has been assumed that the hub height is equal to the rotor diameter. Rotor diameter is scaled at a constant ratio of swept rotor area to turbine power, and turbine ratings of 3 MW, 5 MW and 7.5 MW are addressed. The specifications delineated herein are applicable to each of these ratings, except where noted.

This document is specifically ***not*** intended as a procurement specification, and, thus, does not address manufacturing, quality assurance, documentation, shipping and after-sales service requirements. Such requirements on the component suppliers will be addressed in procurement specifications to be developed in later phases of the LSWT program.

2.0 Applicable Codes and Standards

ANSI/IEEC C37.06-2000	AC High Voltage Circuit Breakers Rated on a Symmetrical Current Basis -- Preferred Ratings and Related Required Capabilities.
ANSI/IEEE C57.12.26-1992	Requirements for Pad-Mounted, Compartmental-Type, Self-Cooled, Three-Phase Distribution Transformers for Use with Separable Insulated High-Voltage Connectors.
AWEA FERC Filing of 5/20/2004	Petition For Rulemaking/Request For Clarification Of FERC Order 2003-A (a.k.a. proposed "Grid Code" for Wind Turbines)
E.ON Netz GmbH	Grid Code for High and Extra High Voltage, Version of 8/1/2003.
IEC 60034-1:2004	Rotating Electrical Machines - Part 1: Rating and Performance
IEC 60470:2000	High Voltage Alternating Current Contactors and Contactor-Based Motor Starters
IEC 60529:2001	Degrees of Protection Provided by Enclosures (IP Code).
IEC 61400-21:2001	Wind Turbine Generator Systems - Part 21: Measurement and Assessment of Power Quality Characteristics of Grid Connected Wind Turbines
IEC 62271-100:2003	High Voltage Switchgear and Controlgear - Part 100: High Voltage AC Circuit Breakers
IEEE 519-1992	Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems
IEEE 48-1990	Test Procedures and Requirements for High Voltage Alternating Current Cable Terminations
NEMA 250-2003	Enclosures for Electrical Equipment (1000 Volts Maximum)
NEMA ICS3-2000	Medium Voltage Controllers Rated 2001 to 7200 Volts AC
NEMA MG1-2003	Motors and Generators
NEMA WC58-1997 (ICEA S-75-381)	Portable and Power Feeder Cables for Use in Mines and Similar Applications
NEMA WC74-2000 (ICEA S-93-639)	5-46 kV Shielded Power Cable for Transmission and Distribution of Electric Energy
NFPA 70-2002	National Electric Code
UL 347	High Voltage Industrial Control Equipment
UL 1072	Medium Voltage Power Cables

3.0 General System Description

The medium voltage electrical drive system is depicted in block diagram form in Figures 2 and 3, below, for two different inverter topologies. For either topology, the major subsystems consist of a single synchronous generator, a rectifier assembly, DC power distribution, an inverter assembly, AC power distribution and a transformer/switchgear assembly.

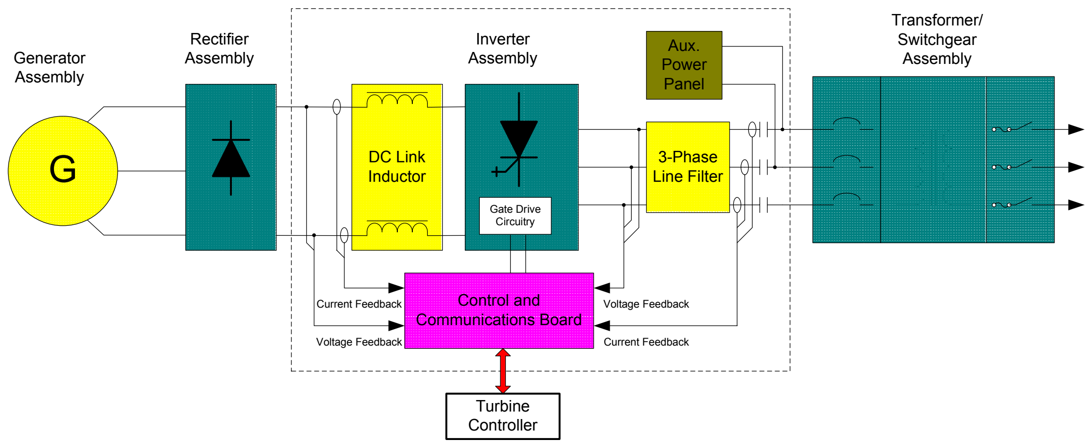

Figure 2. System Block Diagram with Current Source Inverter

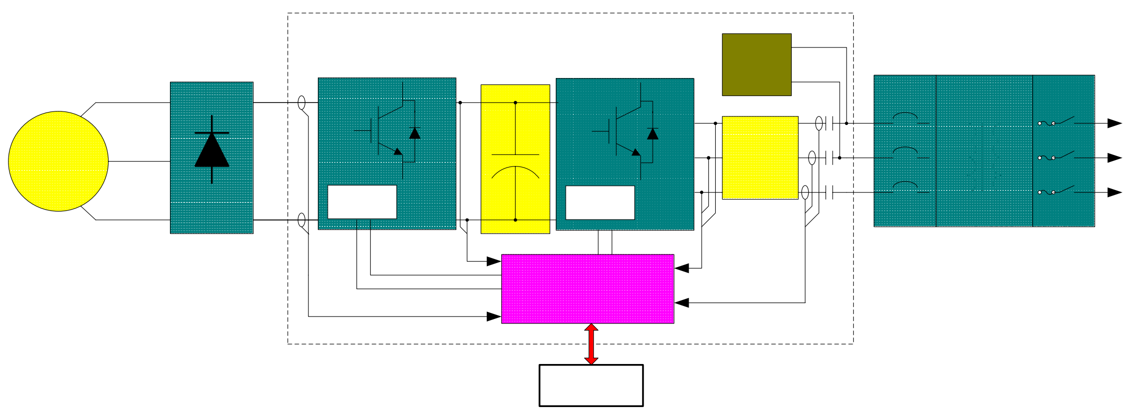

Figure 3. System Block Diagram with Voltage Source Inverter

The synchronous generator, which may be either permanent magnet or wound field excited, operates with approximately constant volts per hertz open circuit voltage over its entire speed range. The AC terminal voltage of the generator is then primarily influenced by this no-load speed voltage and the voltage drop across the generator's synchronous reactance under load.

Generator torque is controlled by regulating the rectifier output current with the inverter in response to an external torque control signal (provided by a turbine master controller, for example).

Power factor at the turbine output is controlled by phase displacing the current waveform generated at the inverter output terminals from the line voltage. The inverter is programmed to either dynamically perform this phase displacement in response to an external power factor or reactive power control signal or through a static power factor or reactive power setting implemented in the inverter control firmware.

4.0 General Environmental Requirements

The following environmental requirements apply to each of the major subsystems of the electrical drive system:

4.1 Altitude: Sea level to 2000 meters.

4.2 Humidity: Up to 100%, condensing.

4.3 Operating Ambient Temperature: -30° to +45°C

4.4 Non-Operating Ambient Temperature: -40° to +45°C

4.5 Contamination: All drive system components will be subjected to windblown dust, as well as dripping rain water and gear oil.

4.6 Design Life: A drive systems components shall provide for a minimum 20-year design life.

5.0 Generator

5.1 General Description: The generator shall be either a wound field excited or permanent magnet excited machine. In the event a wound field generator is selected, the generator shall be excited in such a way so as to provide a constant volts/Hz in the open circuit condition. The pole count, and therefore frequency, can vary dependent on the generator design, but it is expected that the pole count will be either four, six or eight poles. Larger pole counts on a permanent magnet machine could be accommodated by the design of the diode bridge assembly.

The generator will be feeding a six pulse, three switch rectifier and the characteristic 5^{th}, 7^{th}, 11^{th}, and 13^{th} harmonics will be present in the generator current waveform. The synchronous reactance of the generator has some latitude and will be discussed later, however, it is important to note that there exist limits on the reactance. The upper reactance is limited by the ability of the generator to provide rated power into a rectifier bridge and the limit on the low end is determined by the short circuit fault torque and current necessary for survival of the gearbox under these fault conditions.

5.2 Construction: The synchronous generator shall be rated at the IP54 level or better. This can be accomplished by means of air-to-air heat exchanger, or a water-to-air heat exchanger. The stator winding shall be of the form wound construction, using all class H materials and with a class B design temperature rise. In the event that a wound field machine is used, the rotor winding shall also use class H materials with a class B rise.

5.3 Nominal Continuous Power Output: Generator shall have a continuous output power rating at nominal speed per Table 1, below.

Turbine Rating	Generator Rating
3 MW	3.2 MW
5 MW	5.3 MW
7.5 MW	8.0 MW

Table 1. Generator Power Ratings

5.4 Speed Range: Generator speed shall vary from a cut-in speed of 600 rpm to a nominal speed of 1200 rpm, with transient overspeed conditions to 1440 rpm, maximum based on a six-pole design.

5.5 Load Profile: The generator load profile is as shown in Figure 3, below. Applied generator torque will vary in proportion to the square of the generator speed from cut-in (T_{ci}) to 100% of rated torque. Generator torque will be reduced above rated speed to provide for constant power operation between rated speed and maximum transient overspeed.

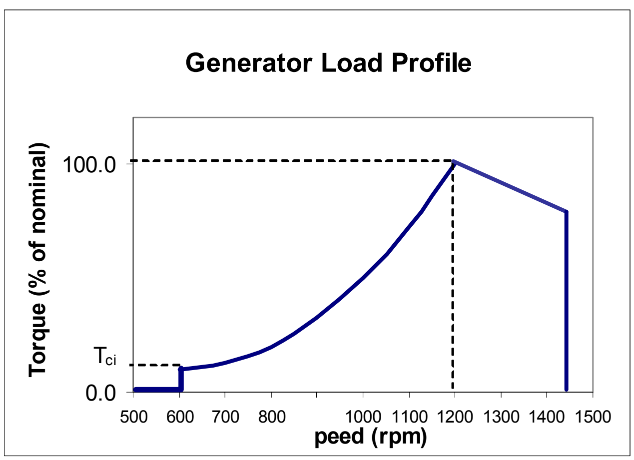

Figure 3. Generator Load Profile Based on 6-Pole Machine

5.6 Efficiency: Generator efficiency shall meet or exceed the efficiency specified in Table 2, below, at each load point.

Load Point	Speed (rpm)	Torque (% nom.)	Power (% nom.)	Efficiency (%)
1	600	T_{ci}	TBD	92%
3	1200	100	100	95%

Table 2. Generator Minimum Efficiency Based on 6-Pole Machine

5.7 Number of Phases: Three.

5.8 Number of Stator Windings: One.

5.9 Stator Phase Connection: Wye connected.

5.10 EMF Voltage Constant: Per Table 3, below.

Turbine Rating	EMF Constant (VAC_{rms}/rpm)
3 MW	1.59
5 MW	2.76
7.5 MW	4.58

Table 3. Generator EMF Constants

5.12 Synchronous Reactance: 0.33 pu, +10%, -0%.

5.13 Shaft Speed Sensing: Not required for torque control. Low resolution speed sensor to be supplied by turbine manufacturer for feedback to turbine master controller.

5.14 Temperature Sensing: Each stator winding shall be equipped with a thermostatic device to indicate excess temperature. Location of the temperature sensing device shall be in the stator slot and not in the end turns.

5.15 Anti-Condensation Heating: Generator shall be equipped with space heaters to prevent condensation during idle periods. If a water-to-air heat exchanger, then water temperature can be used to keep prevent condensation.

6.0 Rectifier

The rectifier assembly, collocated with the inverter assembly at the base of the turbine tower, shall conform to the following:

6.1 Type: Three-phase, six-pulse, controlled (SCR based) bridge rectifier.

6.2 Cooling: Rectifier assembly shall be cooled by either natural or forced air convection.

6.3 Maximum Open Circuit AC Voltage: 96% of nominal AC line voltage.

6.4 Minimum Full Load AC Voltage: 70% of nominal AC line voltage.

6.5 Maximum Continuous AC Current: Per Table 4, below.

Turbine Rating	AC Current (A_{rms})
3 MW	1070
5 MW	1030
7.5 MW	930

Table 4. Rectifier Assembly AC Current Ratings

6.6 AC Frequency Range: 30 to 72 Hz for 6-pole machine.

6.7 Losses: Rectifier SCRs shall be selected such that the rectifier assembly losses do not exceed 0.5% of the turbine output rating at full load.

7.0 Intra-Tower Power Distribution

Intra-tower power cabling includes the medium voltage insulated conductors utilized to transmit power from the generator to the input terminals of the rectifier at the base of the turbine tower. A flexible pendant loop is provided between the generator and a junction box mounted on the interior surface of the tower directly below the yaw bearing. A transition to fixed wiring is made in the junction box to complete the run to the rectifier/inverter assembly.

7.1 Construction: Cable construction shall be per Table 5, below.

Cable Section	Fixed	Pendant
Type	UL Type MV-105	ICEA Type SHD
Voltage Rating	5/8 kV	5/8 kV
Insulation Level	133%	100%
# of Conductors	1	3
Conductors	Copper, compact stranded	Copper, flexible rope-lay stranded
Conductor Shield	Extruded semiconducting EPR	Semiconducting tape
Insulation	EPR	EPDM
Insulation Shield	Copper tape over semiconducting EPR	Tinned copper braid over semiconducting tape
Jacket	UV-resistant, flame-retardant PVC	Thermoset CPE

Table 5. Intra-Tower Power Cable Construction

7.2 Conductor Size: Conductor sizes shall be per Table 6, below.

Turbine Rating	Cable Type	# Conductors per Phase	Conductor Size
3 MW	Fixed	1	900 MCM
	Pendant	1	900 MCM
5 MW	Fixed	1	700 MCM
	Pendant	1	700 MCM
7.5 MW	Fixed	1	900 MCM
	Pendant	1	900 MCM

Table 6. Intra-Tower Power Distribution, Power Cable Conductor Sizes

7.3 Installation:

7.3.1 Fixed Cables: Fixed cables shall run along the inside surface of the turbine tower from inverter assembly to the junction box below the yaw bearing. Cables shall be supported by insulated clamps at distances not greater than NEC Table 300.19(A). Cables shall be terminated at each end with copper compression lugs and IEEE-48 stress cones rated at 5 kV or 8 kV.

7.3.2 Pendant Cables: Pendant cable shall pass through the yaw bearing from the tower junction box to the generator cable termination box. Cable loops shall be of sufficient length to maintain manufacturer's recommended minimum bending radius for the maximum number of yaw rotations in one direction allowed by the turbine master controller. Cables shall be terminated at each end with copper compression lugs and IEEE-48 stress cones rated at 5 kV or 8 kV. Mesh-type cable grips shall be used at each termination.

8.0 Inverter

The inverter assembly, located at the base of the tower (internal to tower assembly), controls generator torque and output power factor. The inverter shall be one of two types: 1) a pulse width modulated (PWM) current-source type utilizing symmetrical gate commutated turn-off (SGCT) thyristors, or 2) a pulse width modulated (PWM) voltage-source (three level) type utilizing high voltage insulated gate bipolar transistors (IGBT) or asymmetrical gate commutated turn-off (GCT) thyristors.

8.1 Packaging: The inverter assembly shall be housed in an electrical enclosure with a minimum NEMA-250 rating of 3R and a minimum IEC-529 IP23 degree of protection. The inverter shall be packaged to meet the construction and safety requirements of UL 347.

8.2 Cooling: Forced air cooling shall be utilized.

8.3 AC Line Voltage and Frequency: Nominal voltage per Table 7, below, 3-phase, 60 Hz nominal. Inverter shall be operable on a continuous basis with a +/- 10% tolerance on voltage and +/3 Hz tolerance on frequency. (See 8.9.3 for additional transient voltage tolerance requirements.)

8.4 Continuous Apparent Power and Current Rating: Per Table 7, below.

Turbine Rating	Apparent Power Rating	Nominal Line Voltage	Current Rating
3 MW	3.5 MVA	2,400 V	840 A
5 MW	5.8 MVA	4,160 V	810 A
7.5 MW	8.8 MVA	6,900 V	740 A

Table 7. Inverter Apparent Power, Voltage and Current Ratings

8.5 Power Factor: Programmable over a range of 0.95 leading to 0.95 lagging.

8.6 Harmonic Distortion: Current harmonics at the primary of the transformer assembly shall comply with the requirements of IEEE Standard 519 and IEC Standard 61400-21.

8.7 Efficiency: Inverter efficiency shall meet or exceed the curve of Figure 4, below.

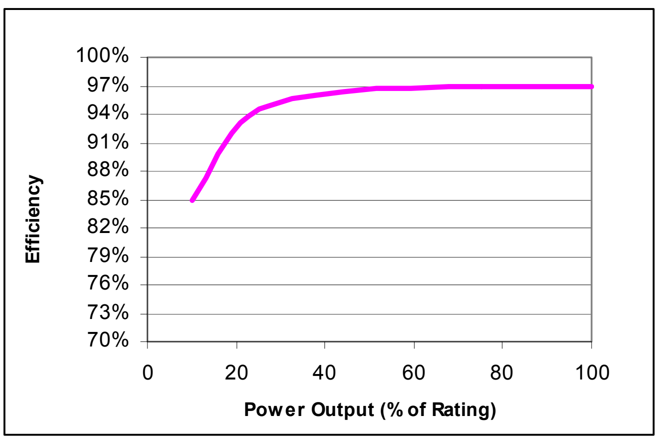

Figure 4. Minimum Inverter Efficiency

8.8 Protective Functions: The inverter shall include the following protection functions:

8.8.1 Gate Drive Fault: Inverter shall trip instantaneously upon receipt of a fault signal from the SGCT driver circuits.

8.8.2 Overtemperature: Inverter shall monitor and provide programmable time delayed tripped on overtemperature on the thyristor/transistor heat sinks and DC and AC filter components.

8.8.3 Overcurrent: Instantaneous short circuit detection shall be provided through the inverter's AC and DC current sensors. (Note: as the inverter is a current limited device, no overload protection is required.)

8.8.4 DC Overvoltage: Inverter shall detect DC overvoltage and include a voltage clamping circuit to limit voltage in the event of a failure in the inverter bridge assembly (current source topology, only).

8.8.5 AC Voltage and Frequency: Inverter shall provide AC voltage and frequency protection with programmable time delays for coordination with the requirements of paragraphs 8.3 and 8.13.3.

8.9 Control: The inverter shall include the following control functionality:

8.9.1 Generator Torque Control: The inverter shall respond to a DC link current control command issued by the turbine master controller via serial communications. The ramp rate on DC link current shall be programmable.

8.9.2 VAR Control: Inverter shall be capable of operation at either constant power factor or constant reactive power, subject to the power factor and apparent power restrictions of 8.4 and 8.5. This capability shall be either locally programmable or in response to an external power factor or reactive power command from the turbine master controller.

8.9.3 Low Voltage Ride Through: In addition to the continuous overvoltage and undervoltage capability described in paragraph 8.3, the inverter shall provide ride-through capability for the wind turbine for transient low voltages that may occur as a result of symmetrical or unsymmetrical faults on the high voltage transmission network. This capability shall meet or exceed the magnitude and duration specified by Figure 5, below.

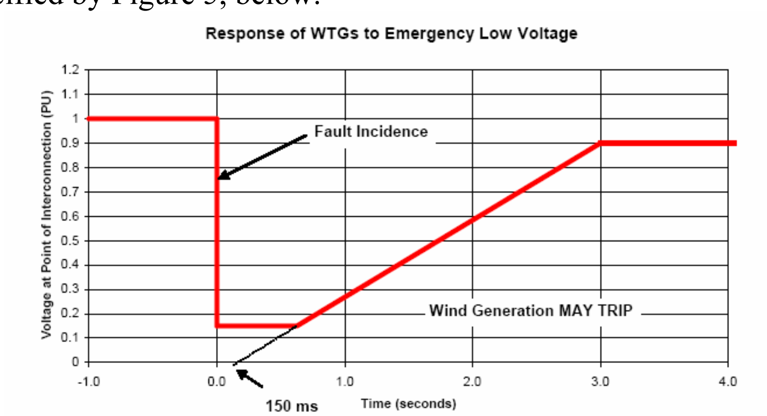

Figure 5. Low Voltage Ride-Through Requirement

During these low voltage transient events, the inverter shall remain operational to its continuous AC current rating, as specified in paragraph 8.4, reducing generator torque (if necessary) to limit AC current.

8.10 Communications and Monitoring

8.10.1 Serial Communications: Inverter communication and control board shall included two serial communications ports, one for communication with the turbine master controller and one for local communication. Each comm port shall have capability for either twisted pair or fiber optic communication media. Capability for implementation of various industry standard protocols (e.g., Modbus, Interbus, CAN, DeviceNet) through firmware changes shall be provided.

8.10.2 Monitored Functions: The following parameters shall be available through serial communications:

- Desired Generator Torque
- Estimated Generator Speed
- Estimated Generator Torque
- DC Link Current or Voltage
- AC Line Currents (3)
- AC Line Voltage (3)
- Output Power
- Output Power Factor
- AC Line Frequency
- Inverter Operating State
- Inverter Fault Codes

9.0 Output Power Cabling

AC output power cabling consists of the insulated conductors utilized to transmit power from the AC output terminals of the inverter assembly to the power circuit breaker located in the transformer assembly. The conductors will be installed in underground duct banks which pass through the tower foundation.

9.1 Construction: Cable construction shall be per Table 8, below.

Type	UL Type MV-105
Voltage Rating	5/8 kV
Insulation Level	133%
# of Conductors	1
Conductors	Copper, compact stranded
Conductor Shield	Extruded semiconducting EPR
Insulation	EPR
Insulation Shield	Copper tape over semiconducting EPR
Jacket	UV-resistant, flame-retardant PVC

Table 8. AC Output Power Cable Construction

9.2 Conductor Size: Conductor size for each phase shall be per Table 9, below.

Turbine Rating	# Conductors per Phase	Conductor Size
3 MW	1	900 MCM
5 MW	1	700 MCM
7.5 MW	1	900 MCM

Table 9. AC Power Distribution, Power Cable Conductor Sizes

9.3 Installation: AC power cables shall be installed in a single rigid nonmetallic conduit encased within the turbine tower foundation. Cables shall be terminated at each end with copper compression lugs and IEEE-48 stress cones rated at 5 kV or 8 kV.

10.0 Transformer

The transformer assembly provides voltage transformation from the inverter output voltage to 34.5 kV (or other wind plant collection system voltage), overcurrent and ground fault protection for the AC system and overcurrent protection and disconnection means for the transformer itself. The transformer assembly is located outside of the base of the turbine tower in a weather and tamper proof outdoor enclosure which complies with the construction requirements of ANSI/IEEE C57.12.26-1992.

10.1 Enclosure: Oil filled, self-cooled (OA), compartmental-type, with separate deadfront primary and secondary compartments.

10.2 Apparent Power Rating: Per Table 10, below.

Turbine Rating	Apparent Power Rating
3 MW	3000 kVA
5 MW	5000 kVA
7.5 MW	7500 kVA

Table 10. Transformer Apparent Power Ratings

10.3 Primary Voltage and Connection: 34.5 kV (150 kV BIL), grounded wye.

10.4 Secondary Voltage and Connection: Per Table 7, above; grounded wye.

10.6 Taps: Four full capacity taps at ±2.5% and ±5% of nominal; external gang operated no-load tap changer located in primary compartment.

10.7 Impedance: 5.75%.

10.8 Temperature Rise: 65°C winding average rise.

10.9 Efficiency: Core losses shall not exceed 0.2% of transformer rating. Full load copper losses shall not exceed 1.0% of transformer rating.

10.10 Coil/Core Construction: Aluminum windings with laminated silicon steel with five-legged core construction.

10.12 Primary Switchgear and Overcurrent Protection: Primary compartment shall be arranged for loop feed, with six universal bushing wells with load break inserts for use with insulated separable connectors. Internal oil immersed cartridge fuses shall be provided for primary overcurrent protection. A single 3-pole gang operated load break oil switch, operable from primary compartment, shall provide for disconnection of the primary winding without interruption of the primary loop.

10.13 Secondary Switchgear: The secondary compartment shall be equipped with a fixed vacuum circuit breaker mounted behind a deadfront panel and wired to the secondary terminals of the transformer. The circuit breaker shall be rated at 5 or 8 kV, with continuous and interrupting current ratings as specified in Table 11, below. The circuit breaker shall be equipped with an integral electronic trip unit with ground fault detection capability.

Turbine Rating	Continuous Current	Interrupting Current
3 MW	800 A	16 kA
5 MW	1200 A	16 kA
7.5 MW	800 A	20 kA

Table 11. AC Power Circuit Breaker Ratings

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NREL Technical Monitor: A. Laxson

14. ABSTRACT *(Maximum 200 Words)*

Kilowatt ratings of modern wind turbines have progressed rapidly from 50 kW to 1,800 kW over the past 25 years, with 3.0- to 7.5-MW turbines expected in the next 5 years. The premise of this study is simple: The rapid growth of wind turbine power ratings and the corresponding growth in turbine electrical generation systems and associated controls are quickly making low-voltage (LV) electrical design approaches cost-ineffective. This report provides design detail and compares the cost of energy (COE) between commercial LV-class wind power machines and emerging medium-voltage (MV)-class multi-megawatt wind technology. The key finding is that a 2.5% reduction in the COE can be achieved by moving from LV to MV systems. This is a conservative estimate, with a 3% to 3.5% reduction believed to be attainable once purchase orders to support a 250-turbine/year production level are placed. This evaluation considers capital costs as well as installation, maintenance, and training requirements for wind turbine maintenance personnel. Subsystems investigated include the generator, pendant cables, variable-speed converter, and padmount transformer with switchgear. Both current-source and voltage-source converter/inverter MV topologies are compared against their low-voltage, voltage-source counterparts at the 3.0-, 5.0-, and 7.5-MW levels.

15. SUBJECT TERMS

wind energy; wind turbines; low wind speed; low wind speed turbine project; variable speed; cost of energy; COE

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